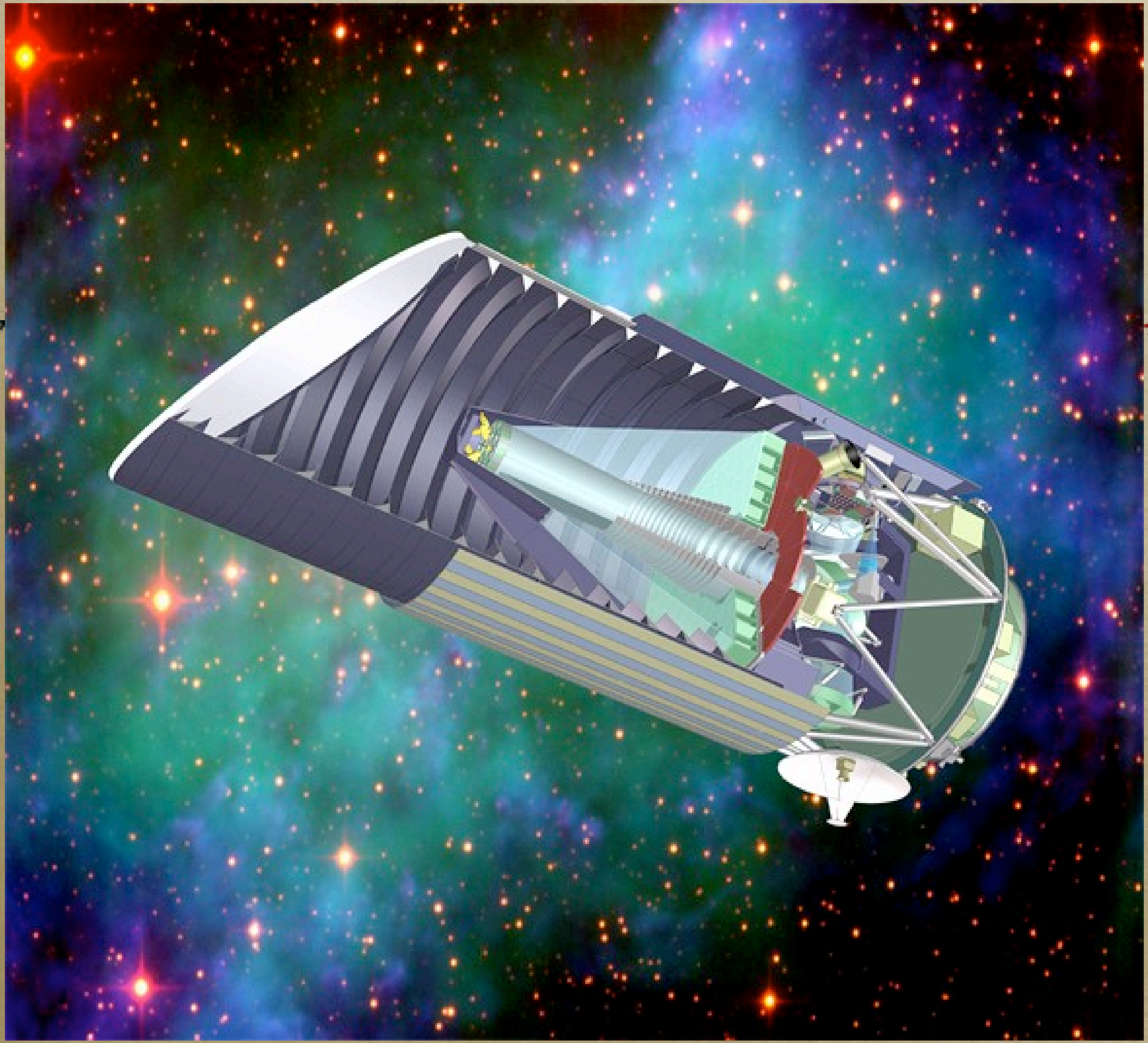
Supernova / Acceleration Probe



Alex Kim

Lawrence Berkeley National Laboratory

Cosmology Theory

- *Kinematics to Dynamics*
- *Cosmological principle: a homogeneous and isotropic Universe can be described by a single function, the scale factor a(t)*
- *Robertson-Walker metric*

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

- *k = -1, 0, 1 for open, flat, or closed geometries*

Friedmann Equations

- *Combine R-W metric and General Relativity to give the equations of motion for a(t)*

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$ *"Newton's Law of Gravitation"*

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho - ka^{-2}$$ *"Conservation of Energy"*

ρ - *Energy density of the Universe's constituents*

p - Pressure of the Universe's constituents

$$p < -\frac{\rho}{3} \rightarrow \frac{\ddot{a}}{a} > 0$$ *Acceleration*

Normal vs Strange

- *Solve Friedmann Equations depending on what the Universe is made of (k=0)*

Non-relativistic matter: $\rho \propto a^{-3}; p = 0 \rightarrow a(t) \propto t^{2/3}$ $\quad \ddot{a} < 0$

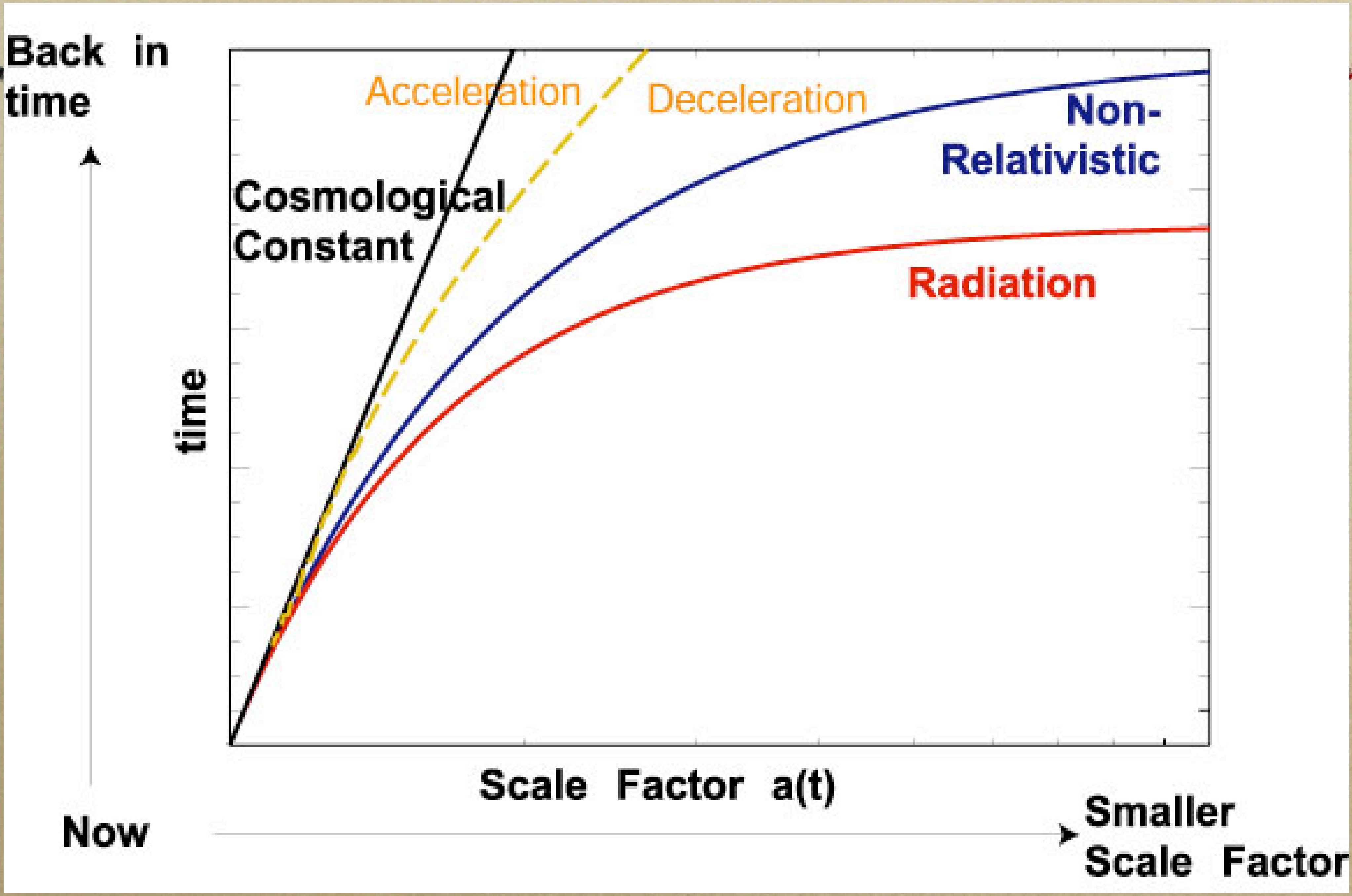
Radiation: $\rho \propto a^{-4}; p = \frac{\rho}{3} \rightarrow a(t) \propto t^{1/2}$ $\quad \ddot{a} < 0$

Dark Energy: $\rho \propto a^{-3(1+w)}; p = w\rho \rightarrow a(t) \propto t^{\frac{2}{3(1+w)}}$

$\ddot{a} > 0 \text{ if } w < -\frac{1}{3}$

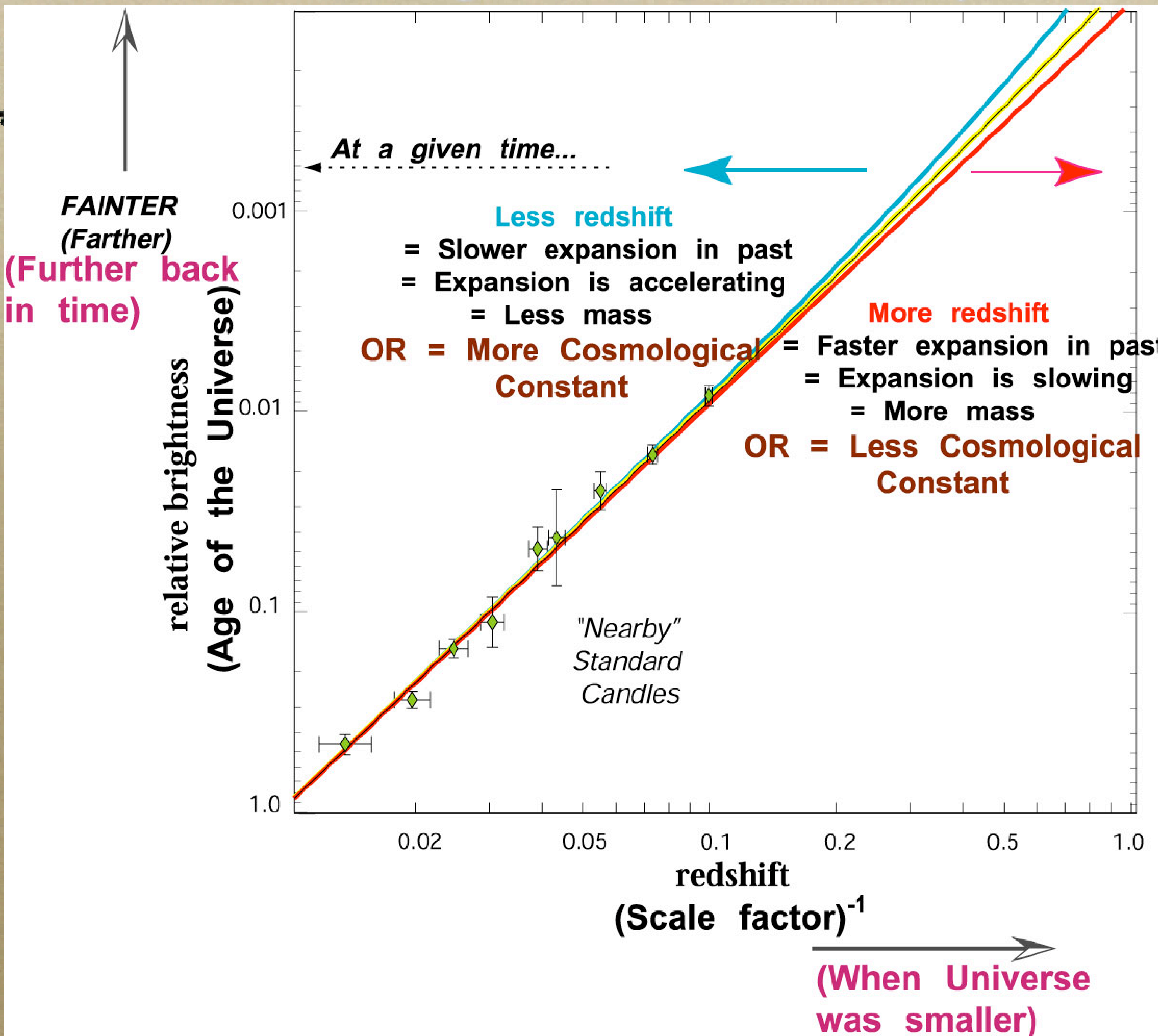
Cosmological Constant w=-1 : $\rho \propto a^{0}; p = -\rho \rightarrow a(t) \propto e^{Ht}$ $\quad \ddot{a} > 0$

Universe Constituents & Dynamics



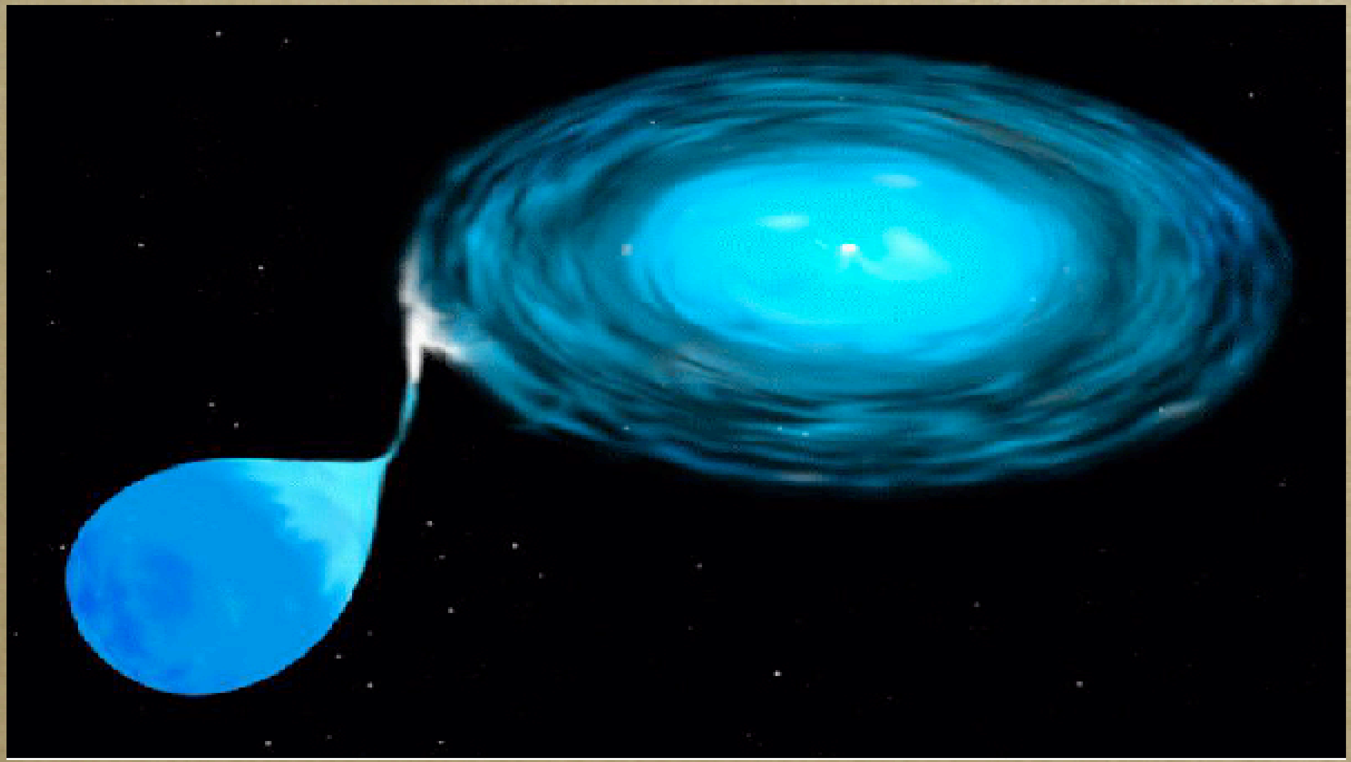
- **By measuring a(t), we can determine the constituents of the Universe, their relative amounts, and properties of the dark energy.**

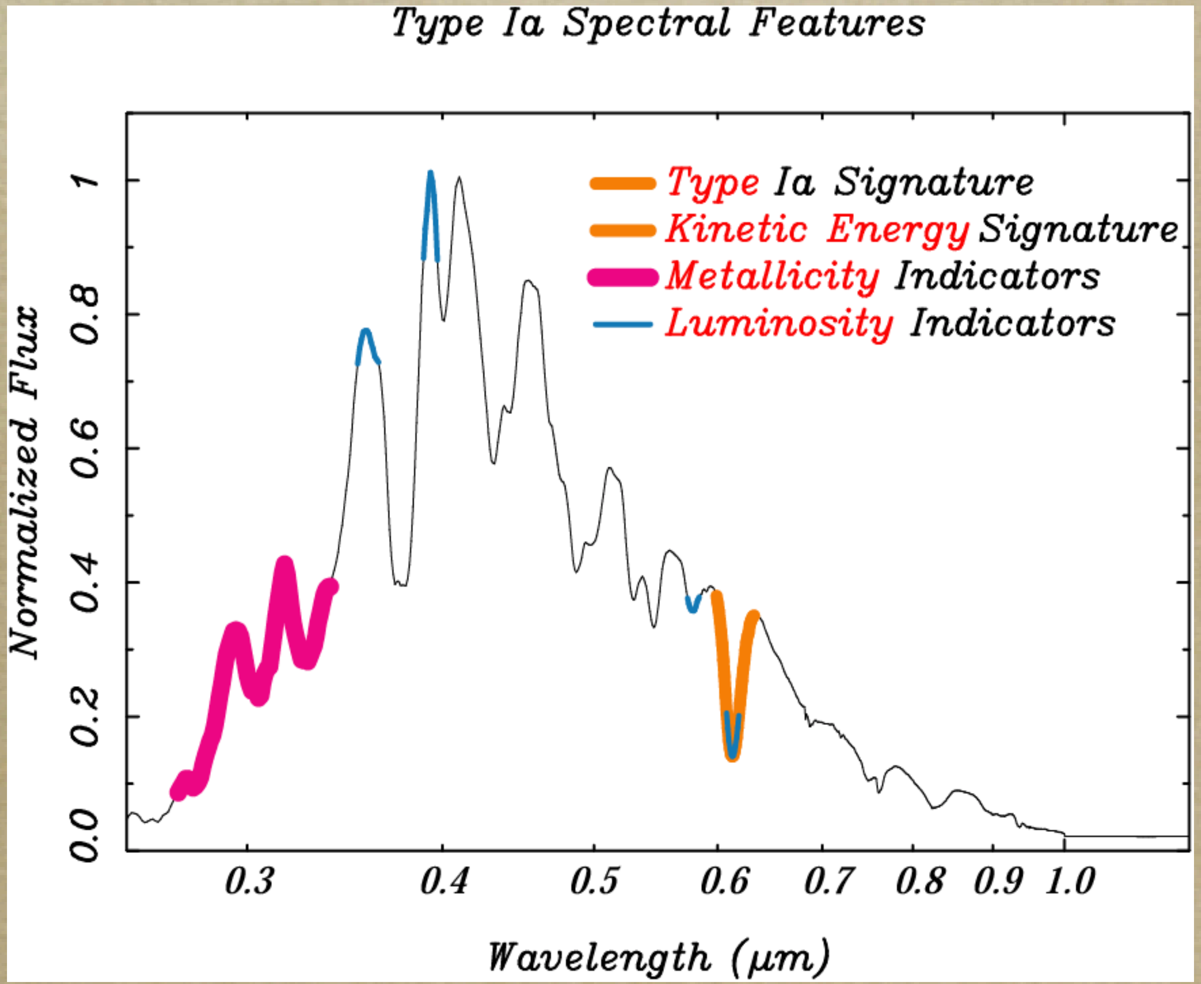
Measuring Universe's History and Fate



Standard Candle: Type Ia Supernovae

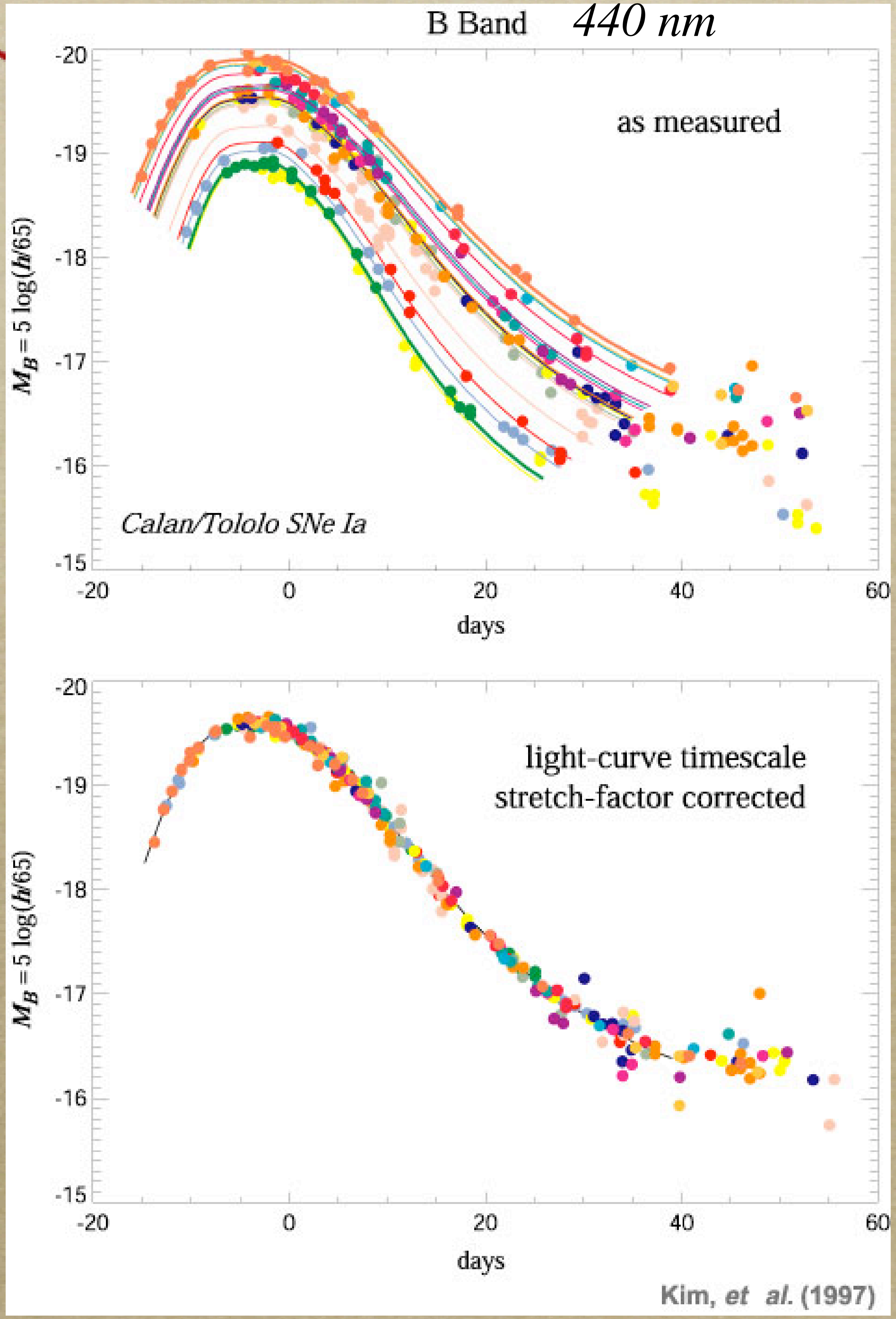
- *Defined empirically as supernovae without Hydrogen but with Silicon*
- *Progenitor understood as a C/O White Dwarf accreting material from a binary companion*
- *As the White Dwarf reaches Chandrasekhar mass, a thermonuclear runaway is triggered*
- *A natural triggered and standard bomb*



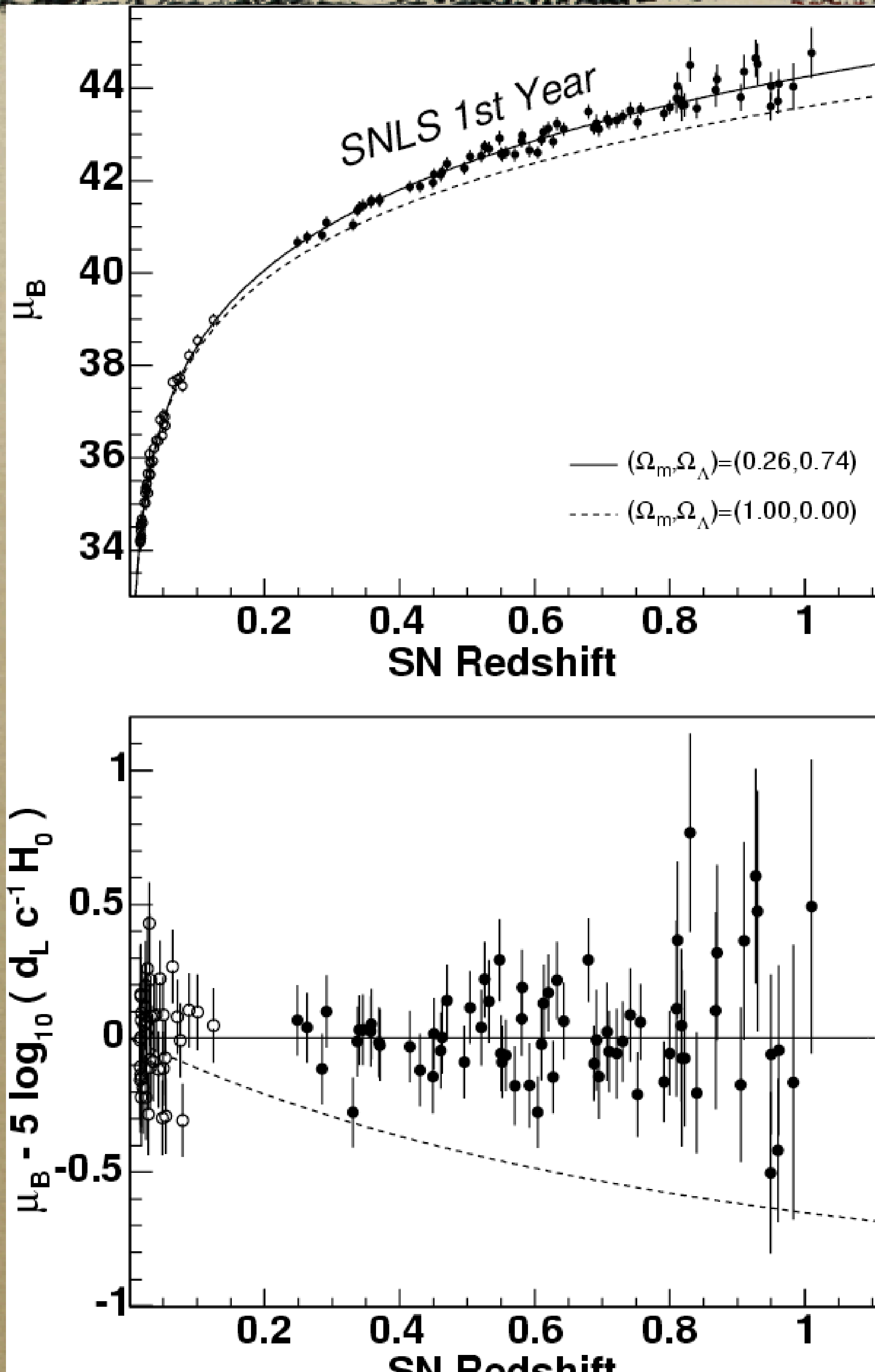


Type Ia Supernovae as Standard Candles

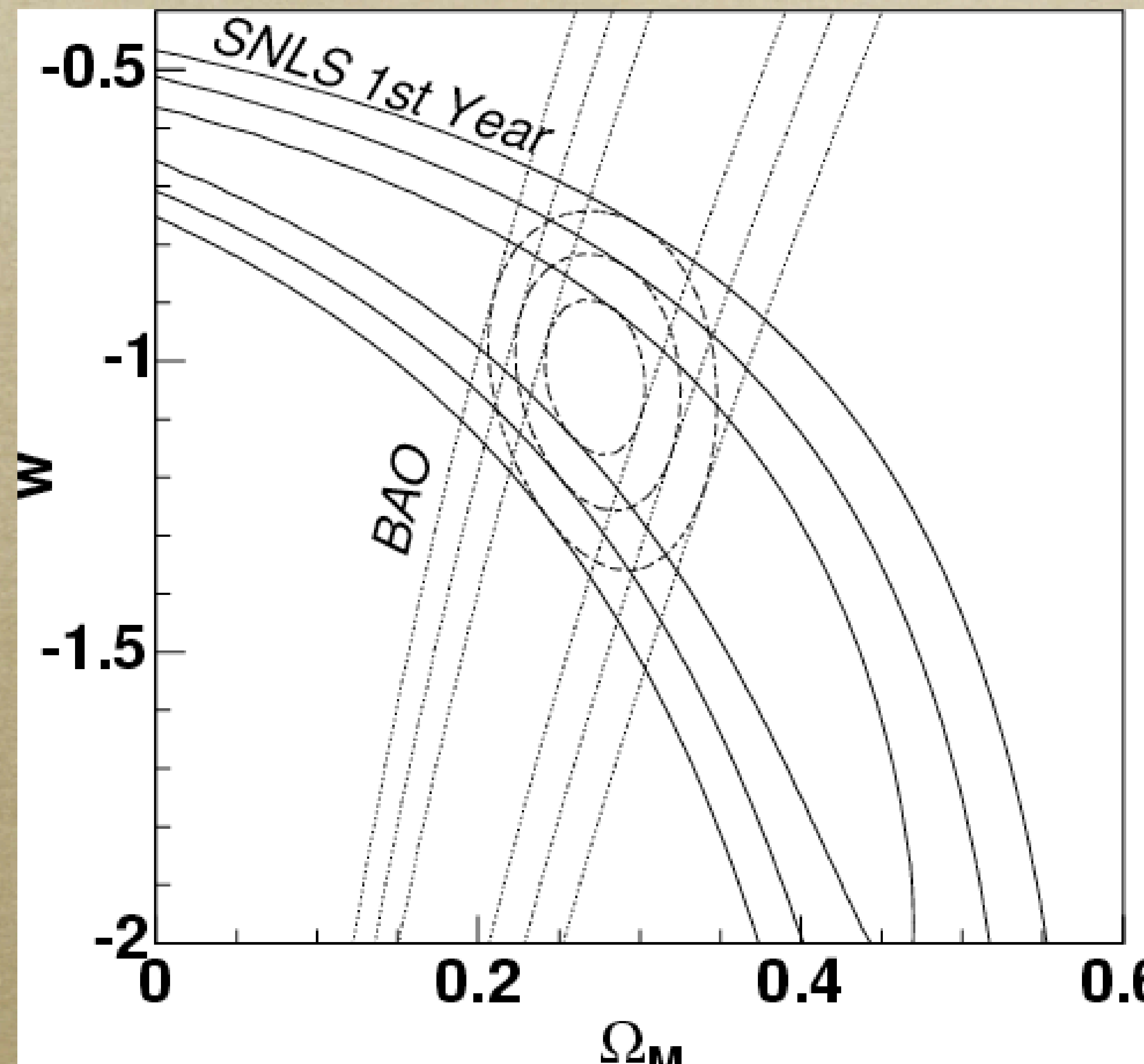
- *After correction for foreground dust, supernovae have peak-magnitude dispersion of 0.25 - 0.3 magnitudes*
- *After correction for light-curve shape supernovae become "calibrated" candles with ~0.15 magnitude dispersion*



Current (Published) Results



Astier et al. (2006)



More Data Coming Soon

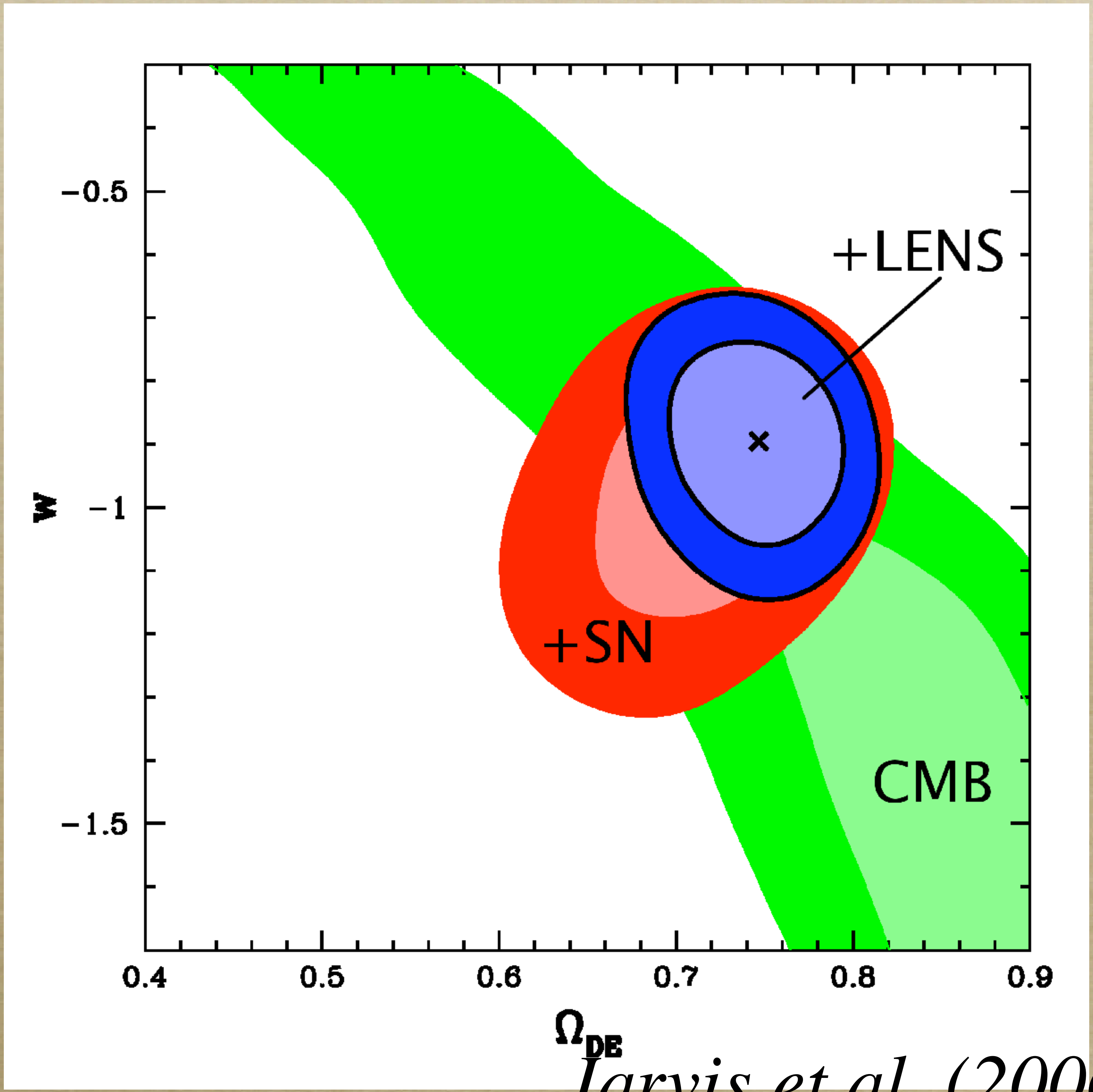
- *High-z Supernovae*
  - *SNLS, Essence, SCP, PANS*
- *Medium-z Supernovae*
  - *SDSS*
- *Local Supernovae*
  - *CfA, KAIT, CSP, SNFactory,...*

Supernovae and Weak Gravitational Lensing Dark Energy Probe

- *Type Ia Supernovae are...*
  - *Pathfinding: Provided the first evidence for the Accelerating Expansion of the Universe*
  - *Sensitive: Give strongest weight in constraining dark-energy parameters today*
  - *Mature: Systematic uncertainties identified, strengths and limitations understood*
  - *Easy: Expansion history only, no structure formation*
- *Weak Lensing*
  - *Established: Ω-w measurements have been made*
  - *Sensitivity: Potentially the most constraining probe of dark energy*
  - *Clean: Galaxy shapes have few/no astrophysical systematics*
- *Together*
  - *Complementary constraints on dark energy parameters*
  - *probe expansion history and growth of structure to distinguish dark energy from modification to GR*

Dark Energy Lensing Results

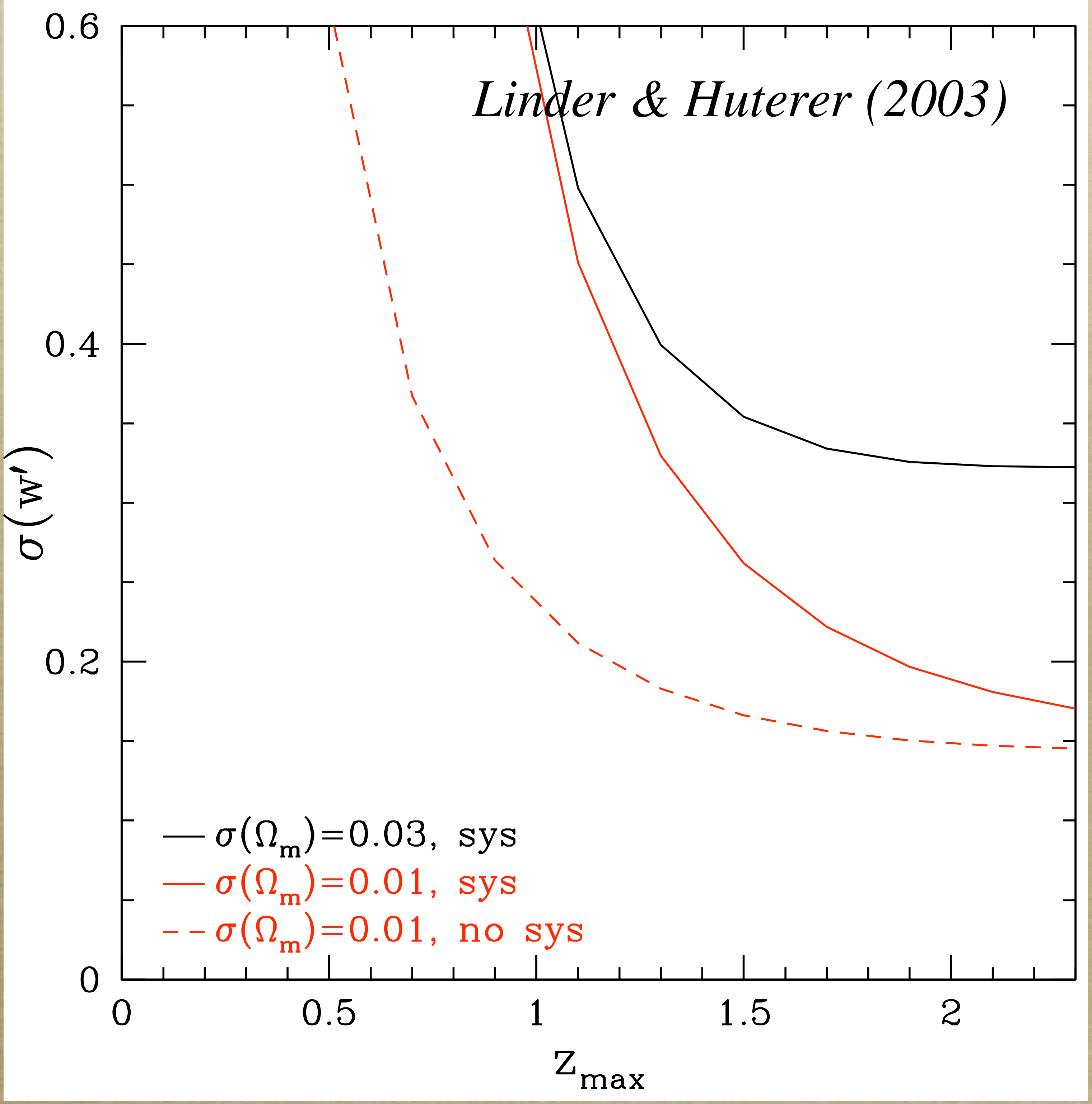
75 square degree CTIO survey



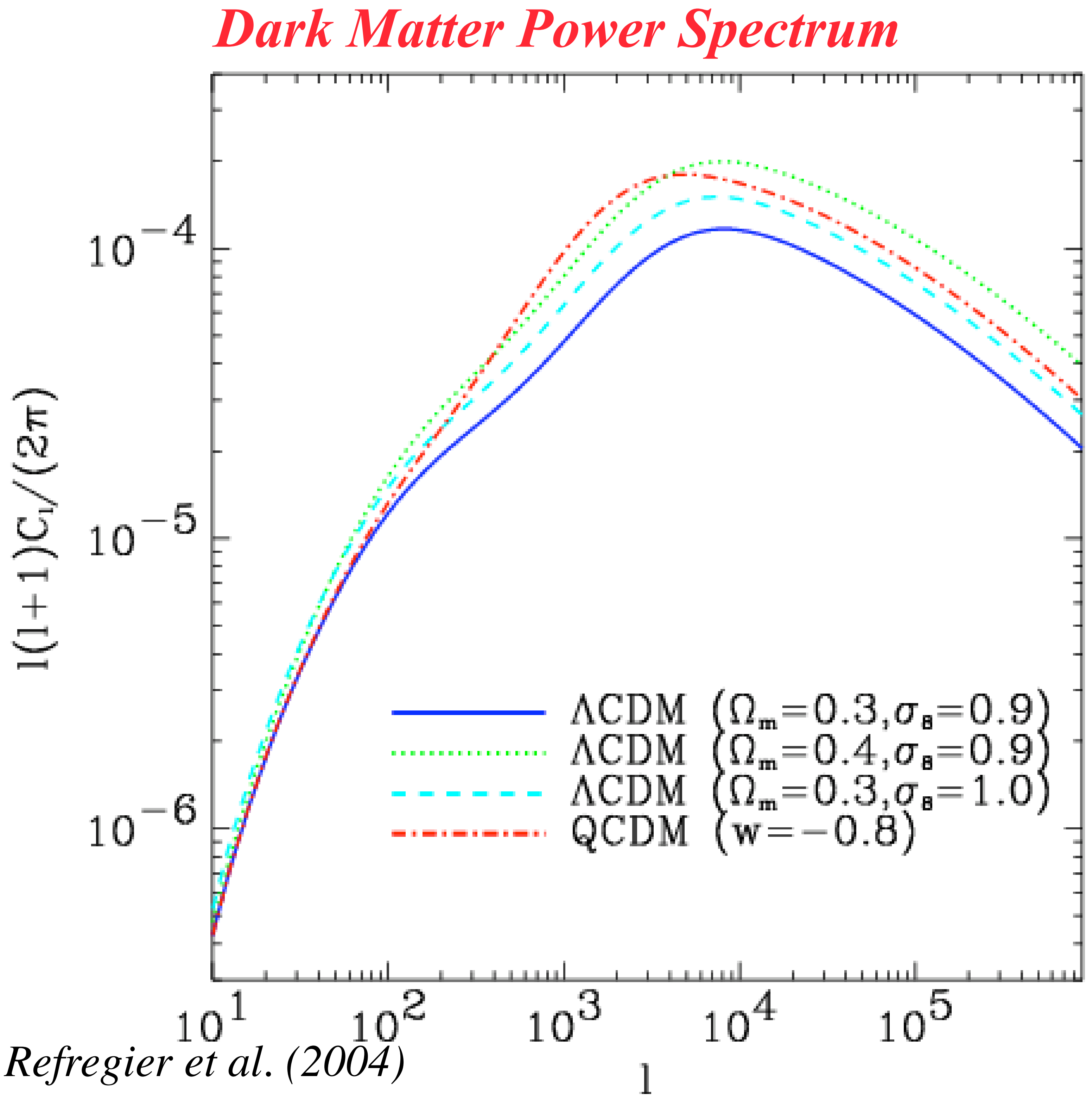
Jarvis et al. (2006)

Improvements in Next Generation Experiments

- *Supernovae at matter-dominated epochs provide significant probative power in the measurement of dark-energy parameters*
- *This is evident when systematic uncertainties are considered*



Improvements in Next Generation Experiments



Refregier et al. (2004)

Probe small angular scales

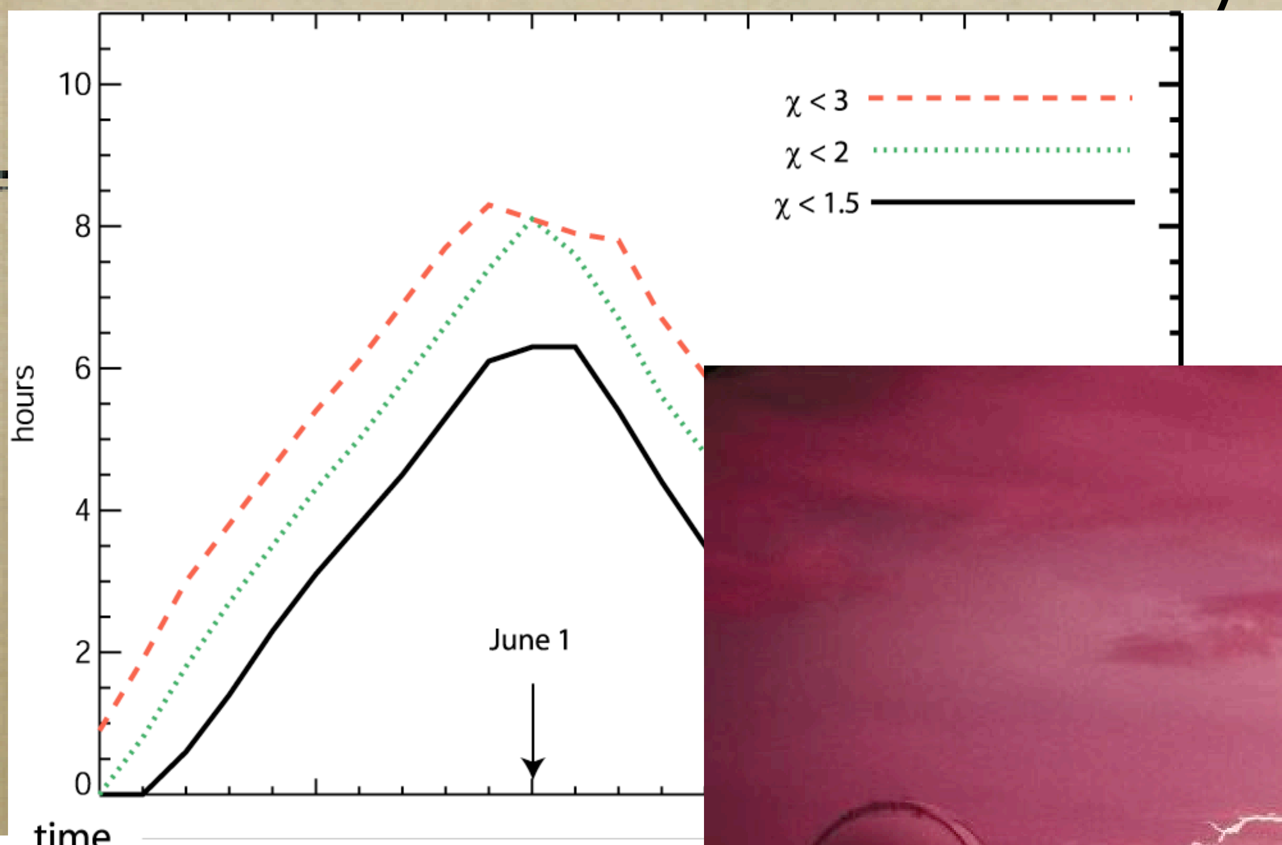
Survey more sky

Statistics and redshift accuracy for bispectrum, cross-correlation cosmography measurements

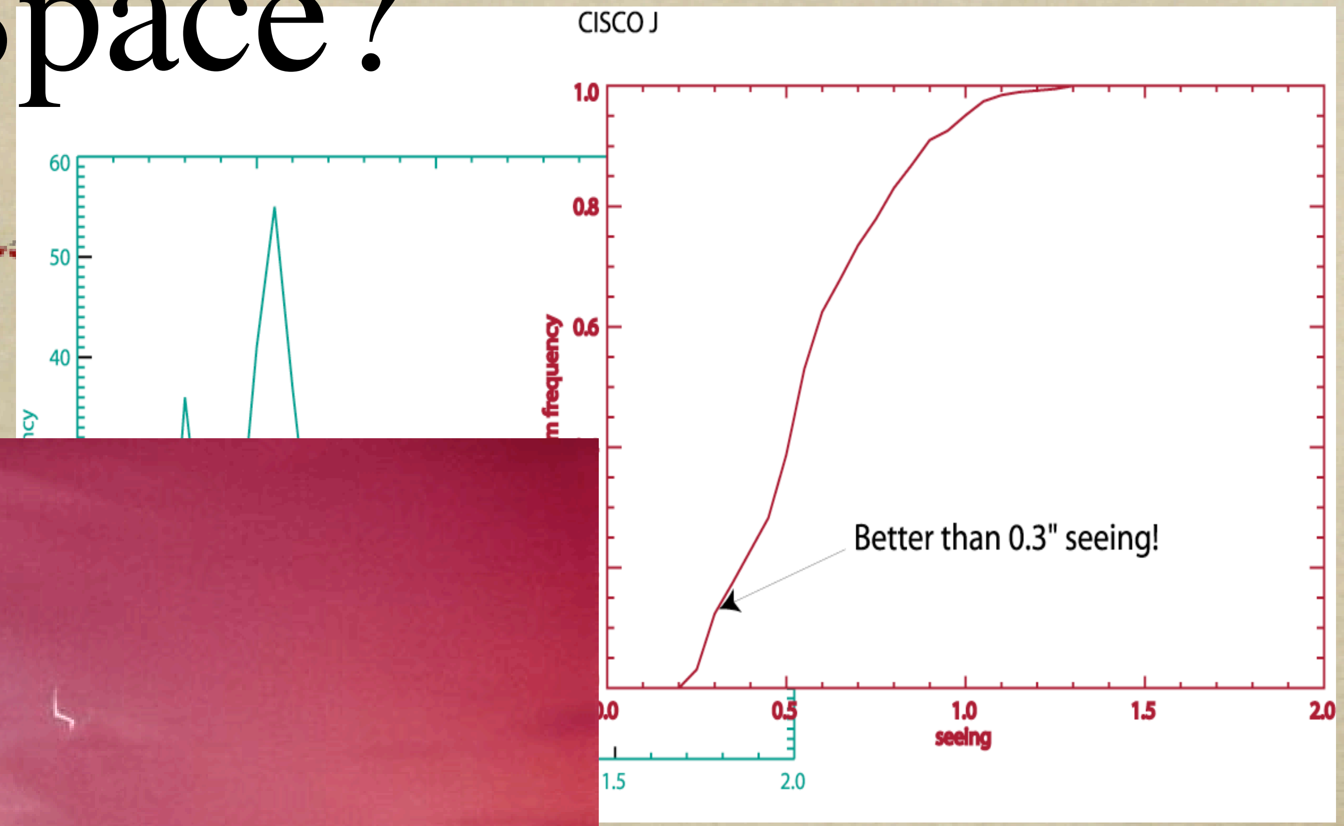
Improvements in Next Generation Experiments

Most Important
Control sources of systematic uncertainty

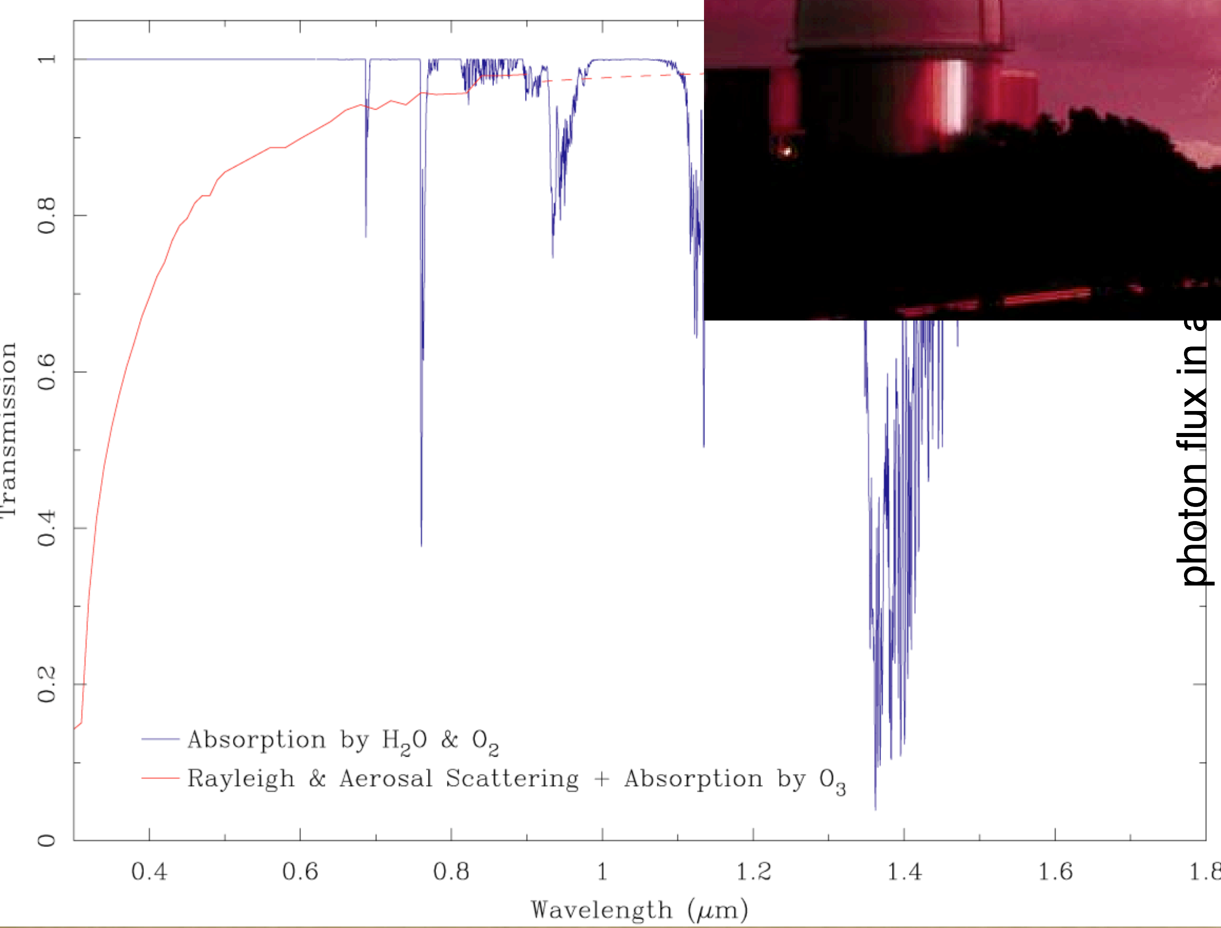
Why Space?



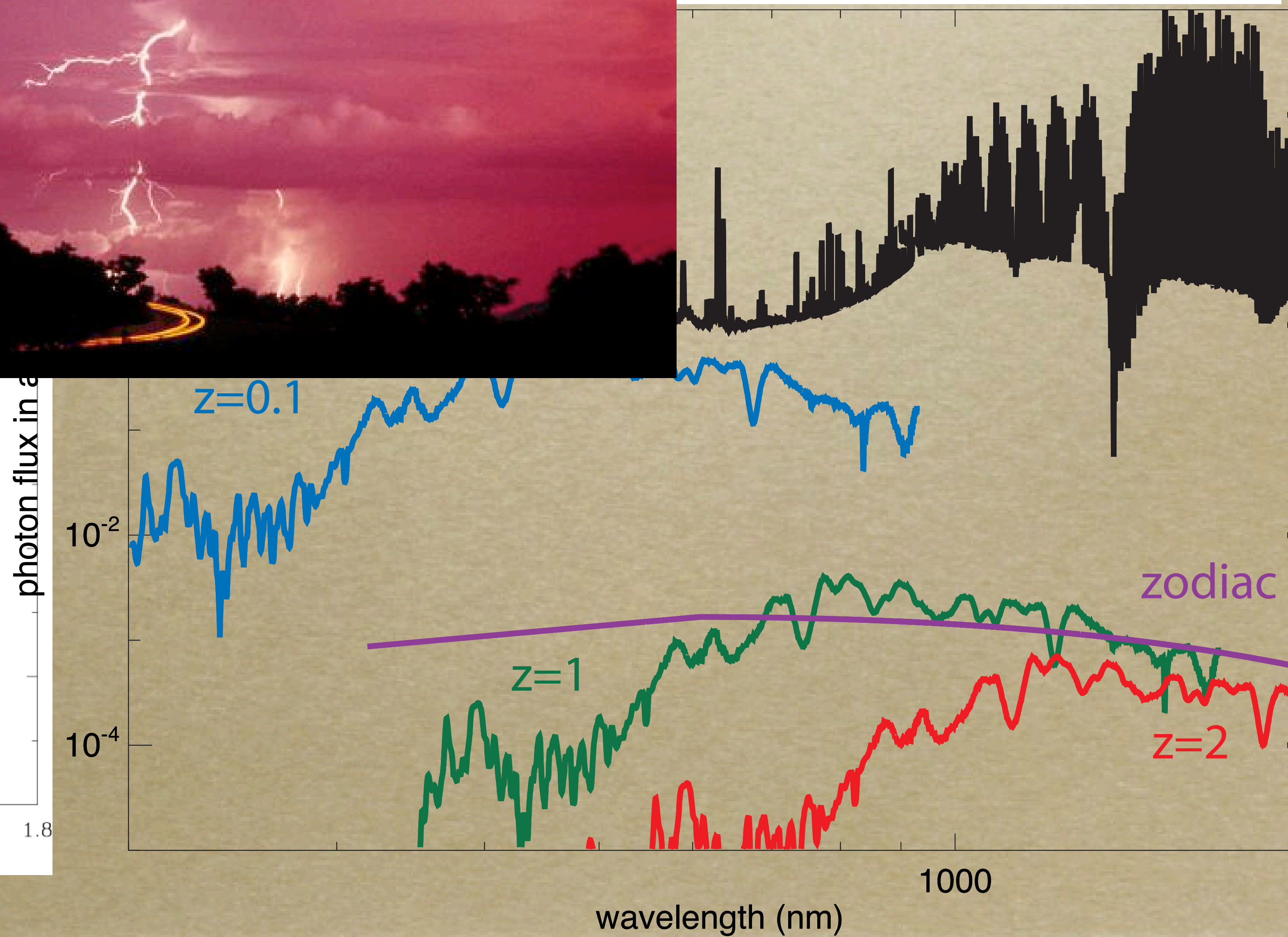
hours
time
June 1
χ < 3
χ < 2
χ < 1.5
0
2
4
6
8
10



CISCO J
Better than 0.3" seeing!
seeing
0.0
0.5
1.0
1.5
2.0
0.6
0.8
1.0



Transmission
Wavelength (μm)
Absorption by H_2O & O_2
Rayleigh & Aerosal Scattering + Absorption by O_3
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8



photon flux in a
wavelength (nm)
1000
10^{-2}
10^{-4}
z=0.1
z=1
z=2
zodiac

SNAP Collaboration

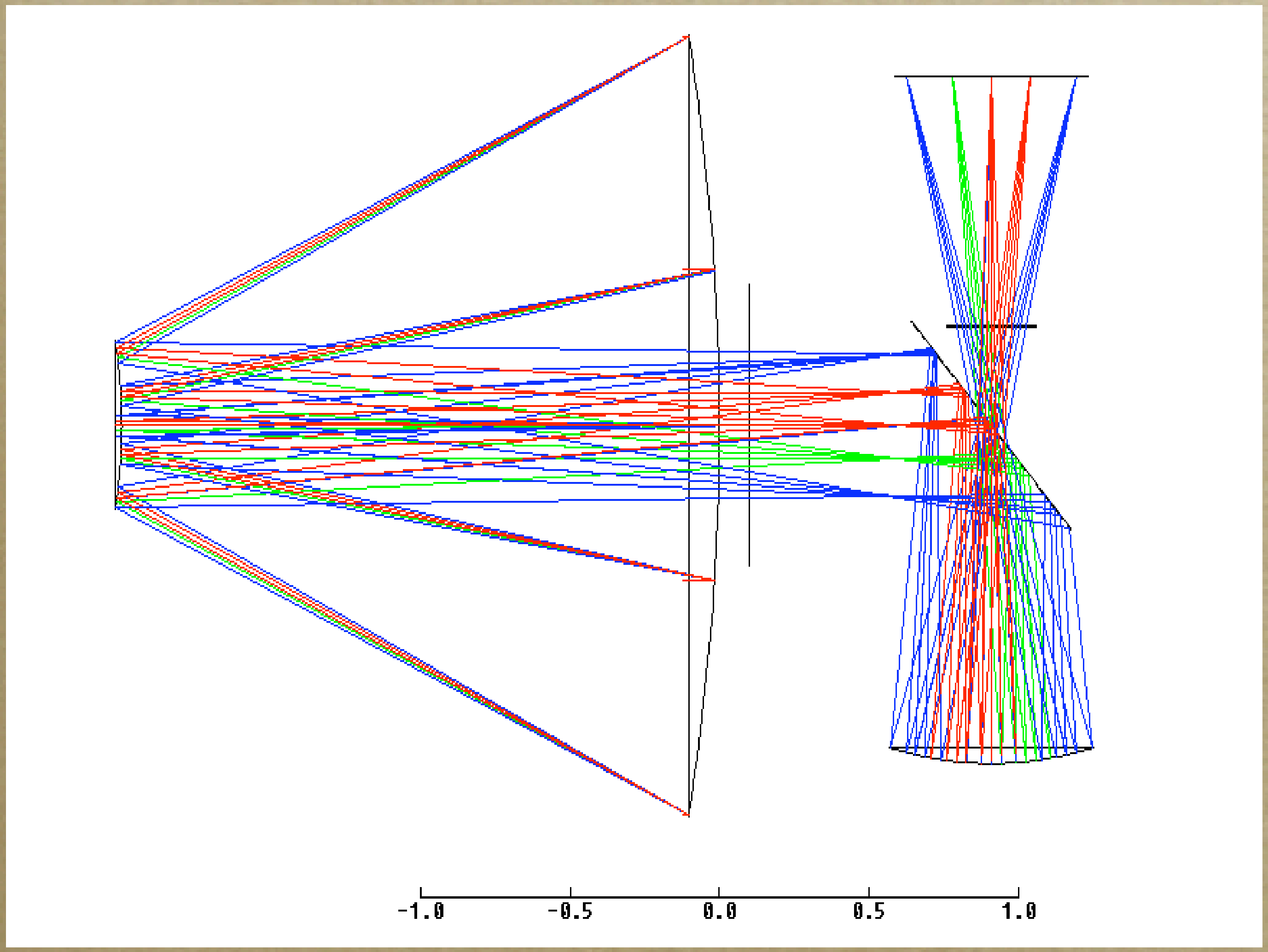
LBNL	G. Aldering, S. Bailey, C. Bebek, W. Carithers, T. Davis[†], K. Dawson, C. Day, R. DiGennaro, S. Deustua[†], D. Groom, M. Hoff, S. Holland, D. Huterer[†], A. Karcher, A. Kim, W. Kolbe, W. Kramer, B. Krieger, G. Kushner, N. Kuznetsova, R. Lafever, J. Lamoureux, M. Levi, S. Loken, B. McGinnis, R. Miquel, P. Nugent, H. Oluseyi[†], N. Palaio, S. Perlmutter, N. Roe, H. Shukla, A. Spadafora, H. Von Der Lippe, J-P. Walder, G. Wang
Berkeley	M. Bester, E. Commins, G. Goldhaber, H. Heetderks, P. Jelinsky, M. Lampton, E. Linder, D. Pankow, M. Sholl, G. Smoot, C. Vale, M. White
Caltech	J. Albert, R. Ellis, R. Massey[†], A. Refregier[†], J. Rhodes, R. Smith, K. Taylor, A. Weintein
Indiana U.	C. Bower, N. Mostek, J. Musser, S. Mufson
IN2P3-Paris -Marseille	P. Astier, E. Barrelet, R. Pain, G. Smadja[†], D. Vincent A. Bonissent, A. Ealet, D. Fouchez, A. Tilquin
Fermi National Laboratory	J. Annis, F. DeJongh, S. Dodelson, T. Diehl, J. Frieman, D. Holz[†], L. Hui, S. Kent, P. Limon, J. Marriner, H. Lin, J. Peoples, V. Scarpine, A. Stebbins, C. Stoughton, D. Tucker, W. Wester
JPL	D. Cole, M. Frerking, J. Rhodes, M. Seiffert
LAM (France)	S. Basa, R. Malina, A. Mazure, E. Prieto
University of Michigan	B. Bigelow, M. Brown, M. Campbell, D. Gerdes, W. Lorenzon, T. McKay, S. McKee, M. Schubnell, G. Tarle, A. Tomasch
University of Pennsylvania	G. Bernstein, L. Gladney, B. Jain, D. Rusin
University of Stockholm	R. Amanullah, L. Bergström, A. Goobar, E. Mörtsell
SLAC	W. Althouse, R. Blandford, W. Craig, S. Kahn, M. Huffer, P. Marshall
STScI	R. Bohlin, D. Figer, A. Fruchter
Yale U.	C. Baltay, W. Emmet, J. Snyder, A. Szymkowiak, D. Rabinowitz, N. Morgan

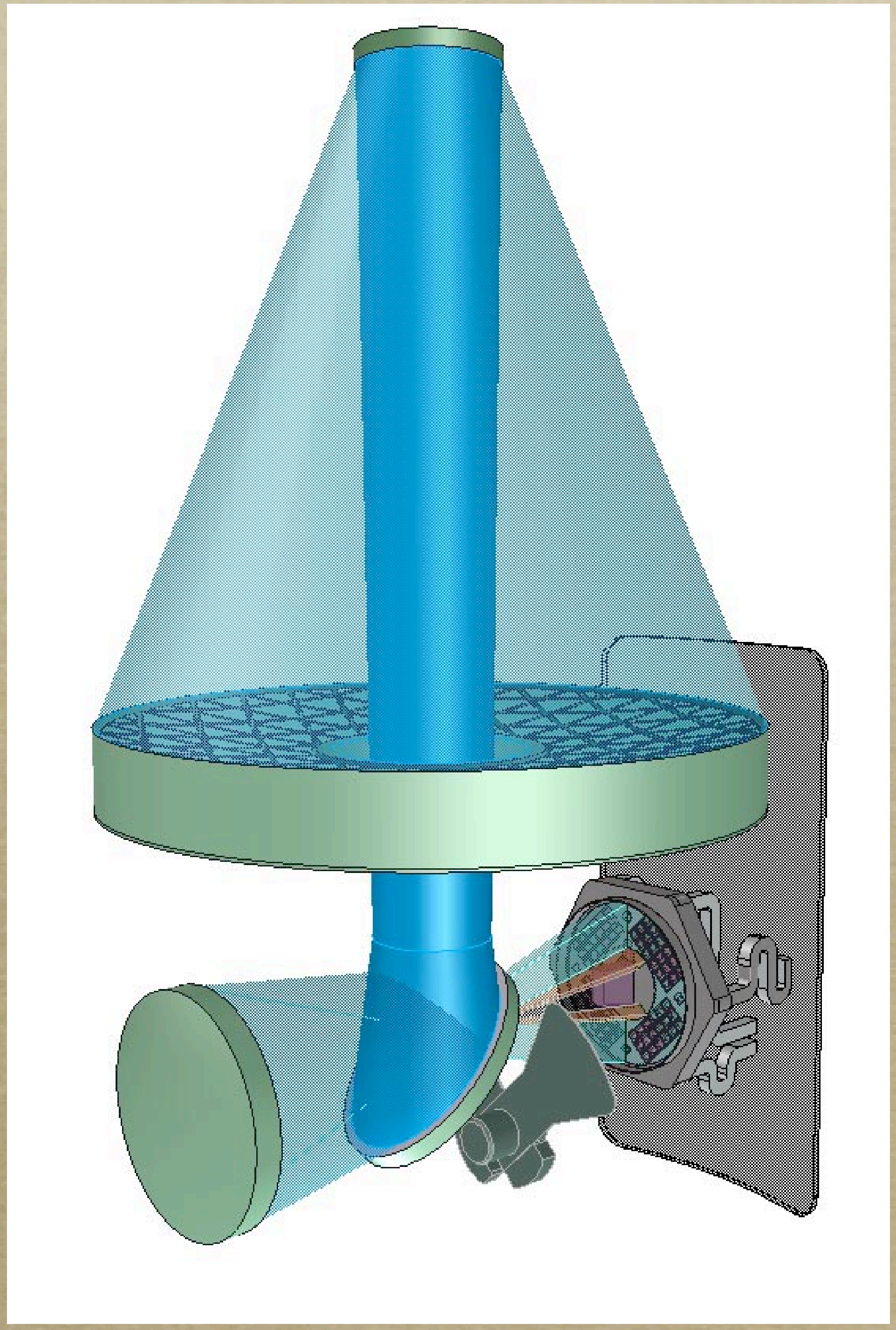
[†]Institutional affiliation

snap.lbl.gov

SNAP Telescope

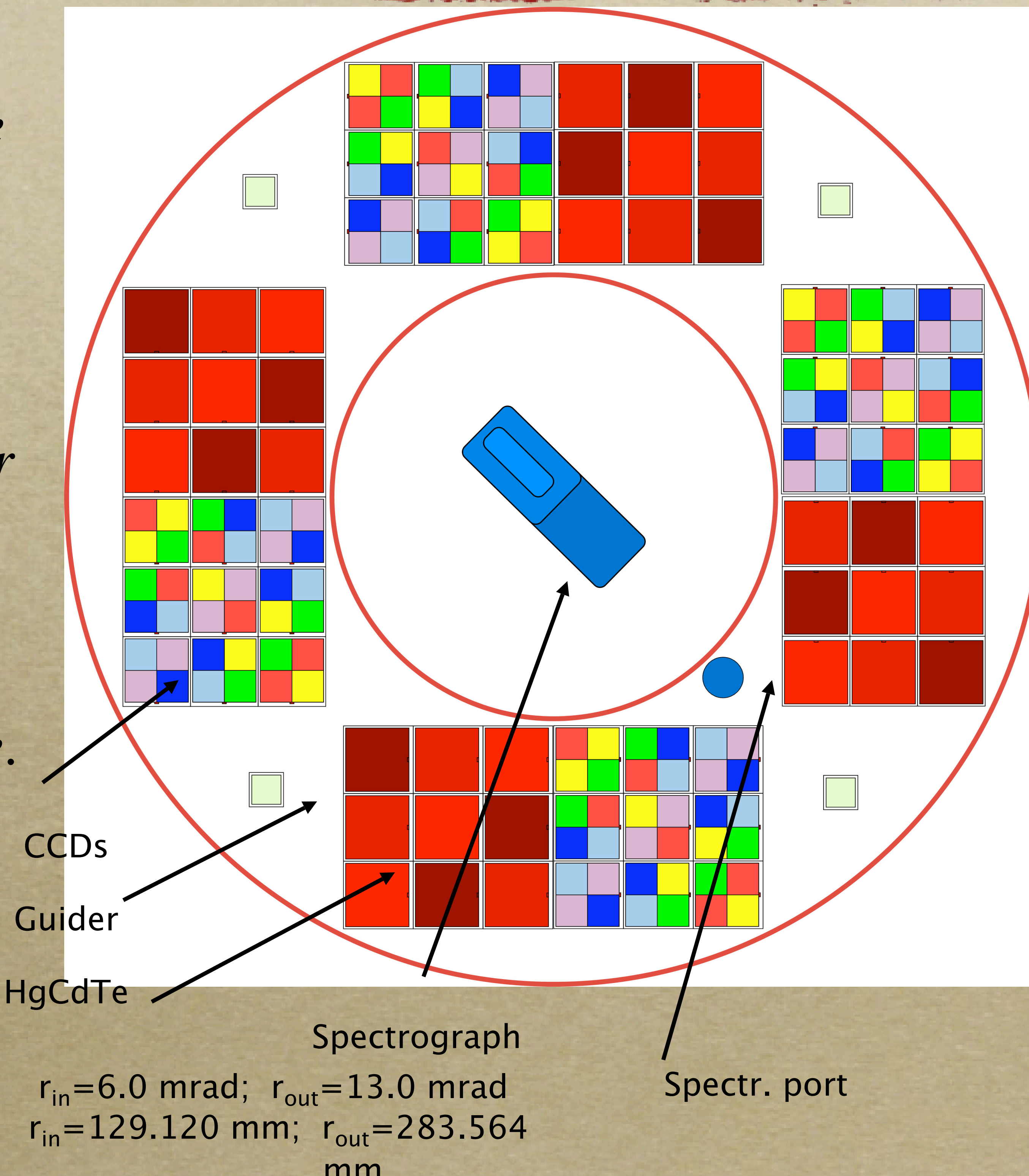
- *2-m primary aperture, 3-mirror anastigmatic design.*
- *Provides a wide-field flat focal plane.*



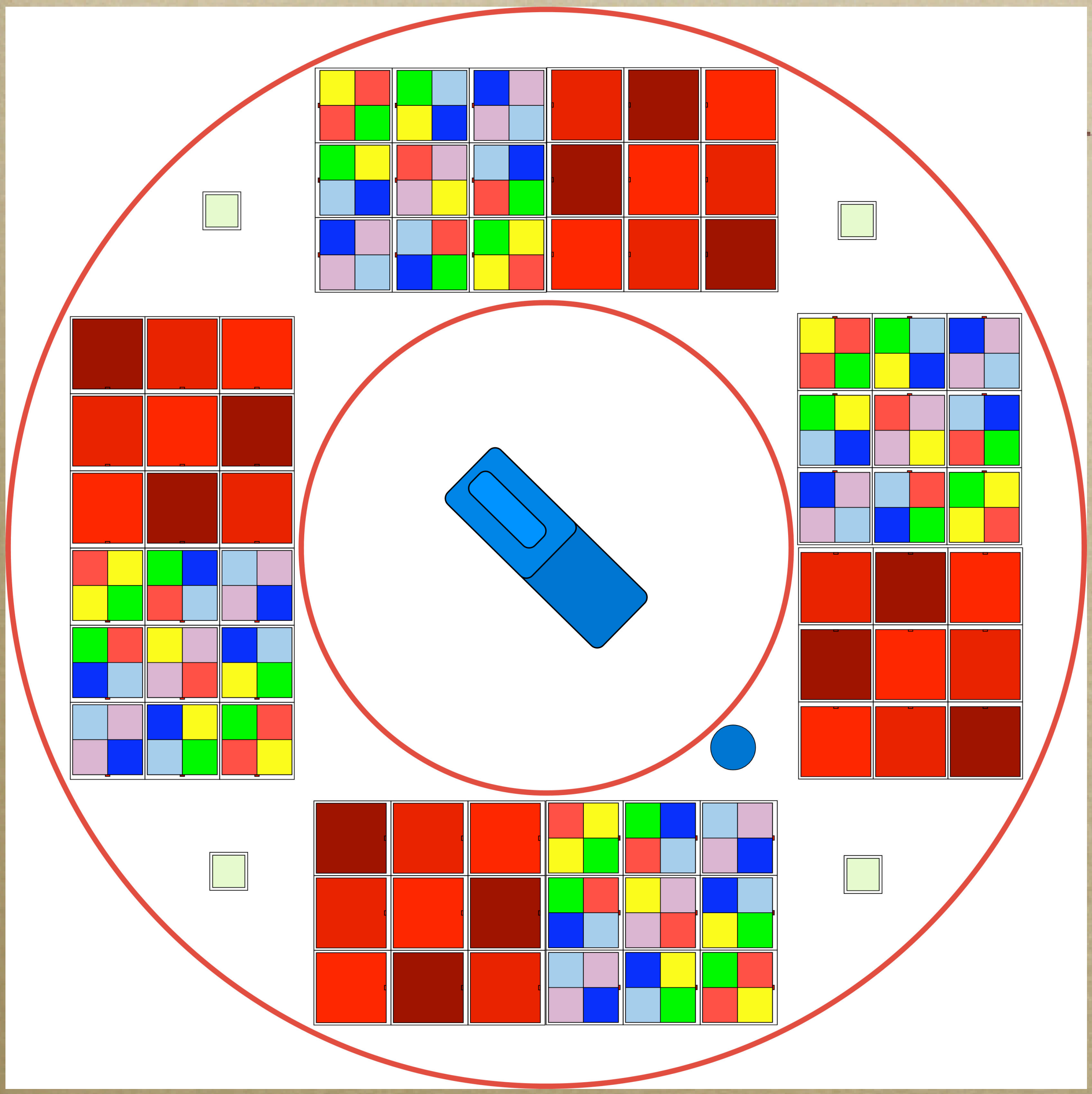


Instrumentation: Imager

- *A large solid-angle camera (0.7 square degrees) provides multiplexed supernova discovery and followup.*
- *Covers wavelength region of interest, 0.35- 1.7 microns.*
- *Fixed filter mosaic on top of the imager sensors.*
  - *3 NIR bandpasses.*
  - *6 visible bandpasses.*
- *Coalesce all sensors at one focal plane.*
  - *36 2k x 2k HgCdTe NIR sensors covering 0.9-1.7 μm.*
  - *36 3.5k x 3.5k CCDs covering 0.35-1.0 μm.*



Instrumentation: Imager

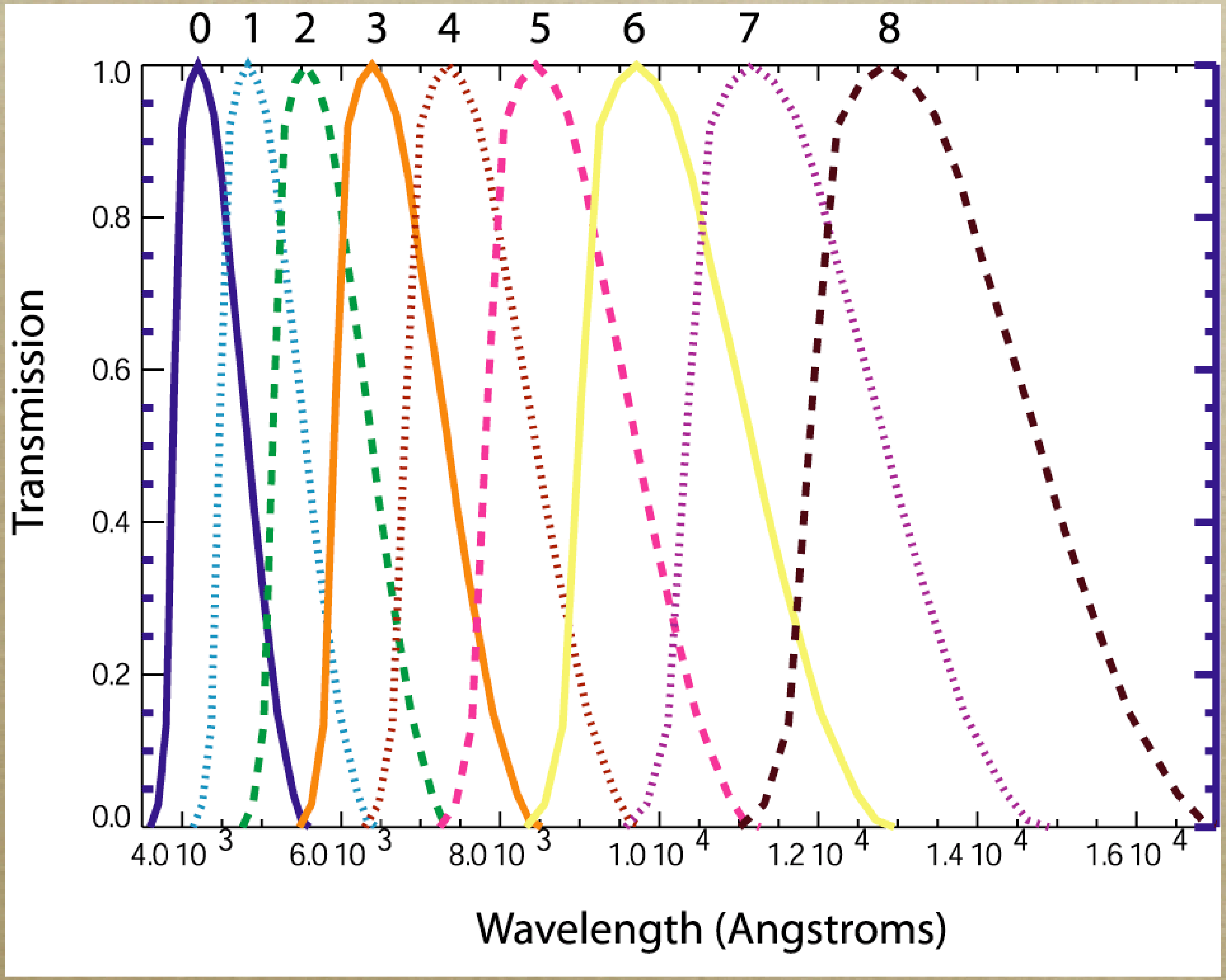


0.7 square degrees
9 passbands
0.35-1.7 microns


REU program, N.A.Sharp/NOAO/AURA/NSF

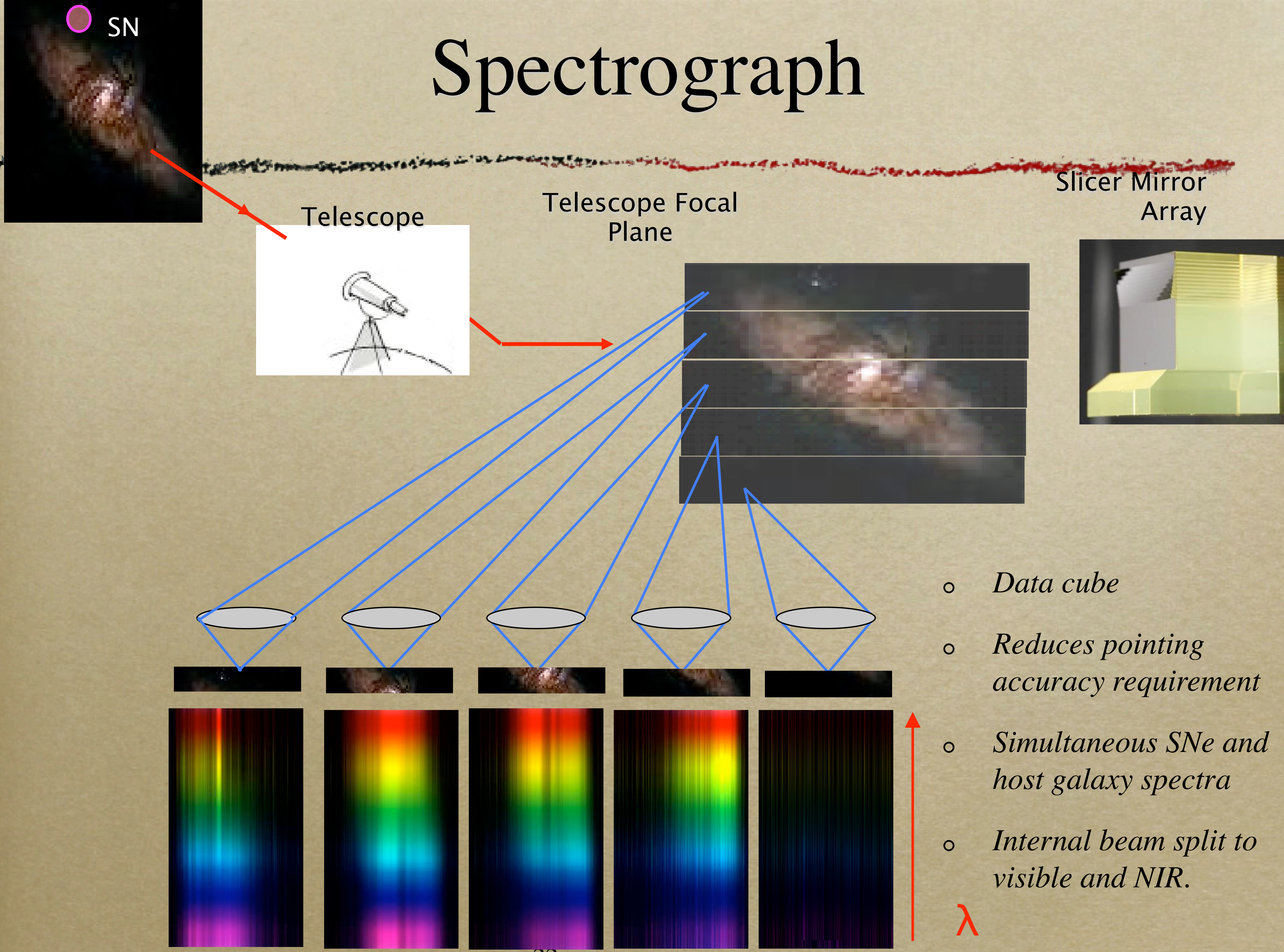
SNAP Filters

- *Sampling meets K-correction requirements (Davis, Schmidt, Kim 2006)*
- *9 redshifted B-band filters distributed logarithmically.*



- *The bluest 6 filters are observed with CCD's, the reddest 3 filters are observed with HgCdTe*

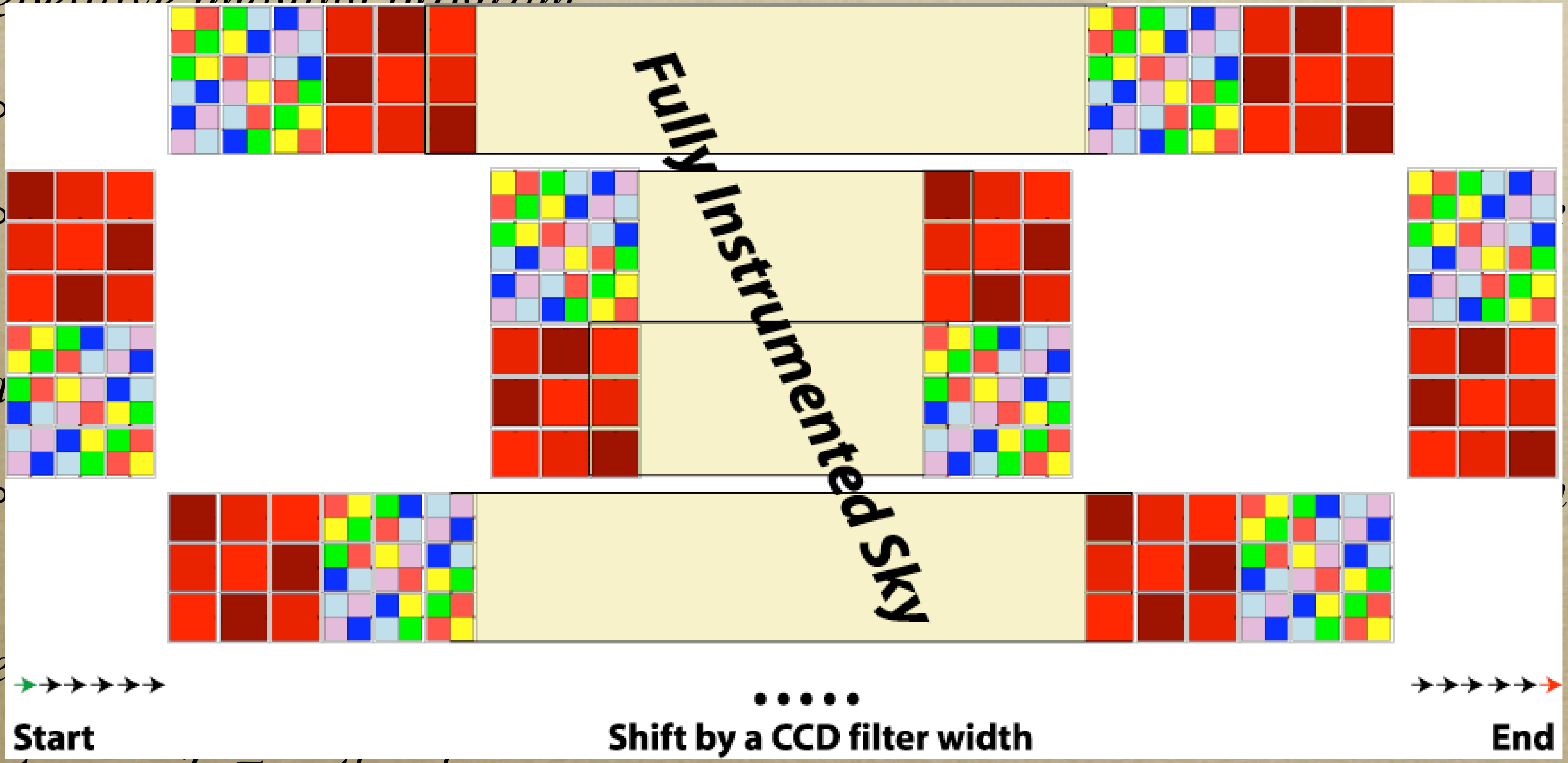
Spectrograph



- *Data cube*
- *Reduces pointing accuracy requirement*
- *Simultaneous SNe and host galaxy spectra*
- *Internal beam split to visible and NIR.*

SNAP Surveys

- *Repetitive imaging program*
  - ○
  - ○ …ry on
- *Ta…*
  - ○ …ear
- *Le…*
- *Extension?: π in the sky*



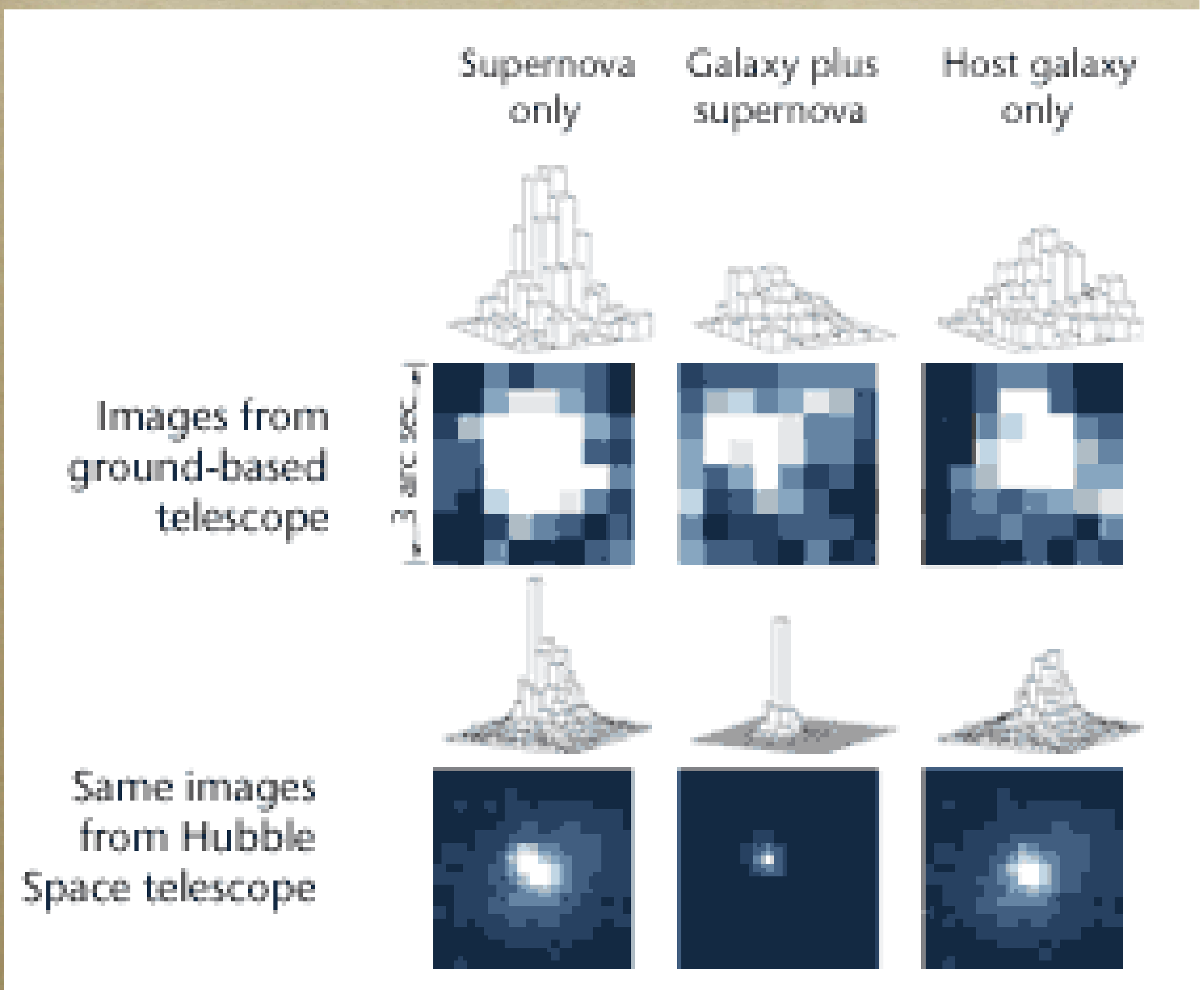
SNAP Survey Depth

Filter	λ_{eff}(Å)	$\Delta\lambda$(Å)	SN Survey (AB mag)		Lensing Survey (AB mag)
			Scan	Co-added Scans	
1	4400	1000	27.9	30.6	28.3
2	5060	1150	27.8	30.5	28.2
3	5819	1323	27.8	30.4	28.1
4	6692	1521	27.7	30.4	28.1
5	7696	1749	27.7	30.3	28.0
6	8850	2011	27.5	30.2	27.9
7	10178	2313	27.5	30.2	27.8
8	11704	2660	27.4	30.1	27.8
9	13460	3059	27.4	30.0	27.7

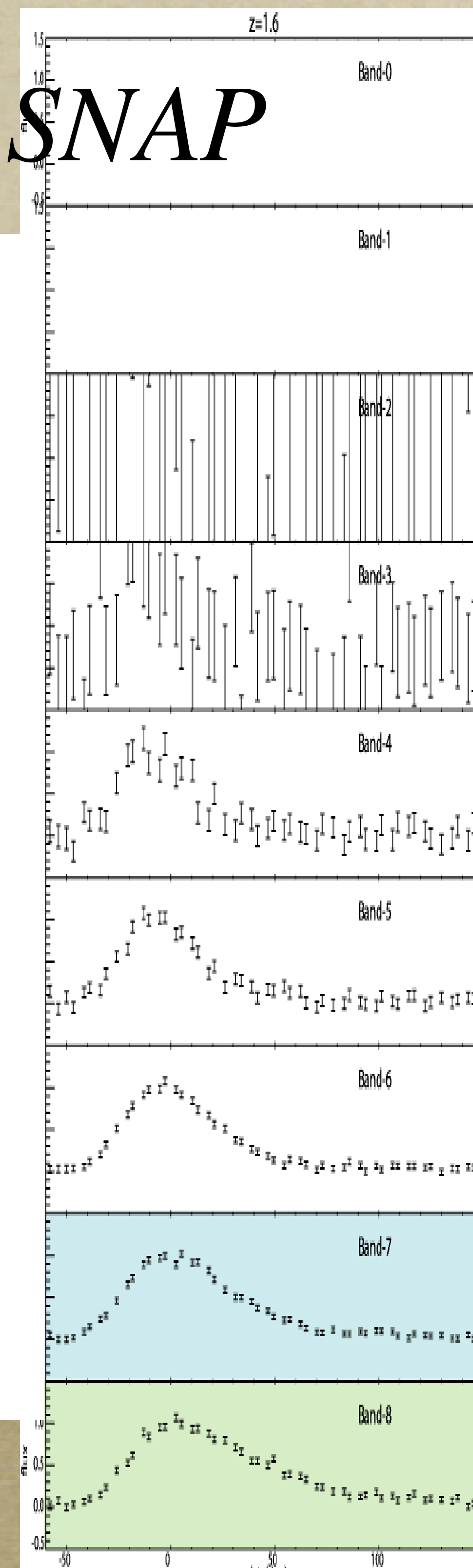
SNAP Data Products

- *Supernovae*
  - *~2000 SNe Ia @ 0.1<z<1.7*
  - *9-band light curves with 4-day cadence*
  - *Spectrum near maximum (triggered)*
- *Weak Lensing*
  - *1000 square degrees*
  - *100 resolved galaxies per square degree*
  - *9-band photo-z determination*

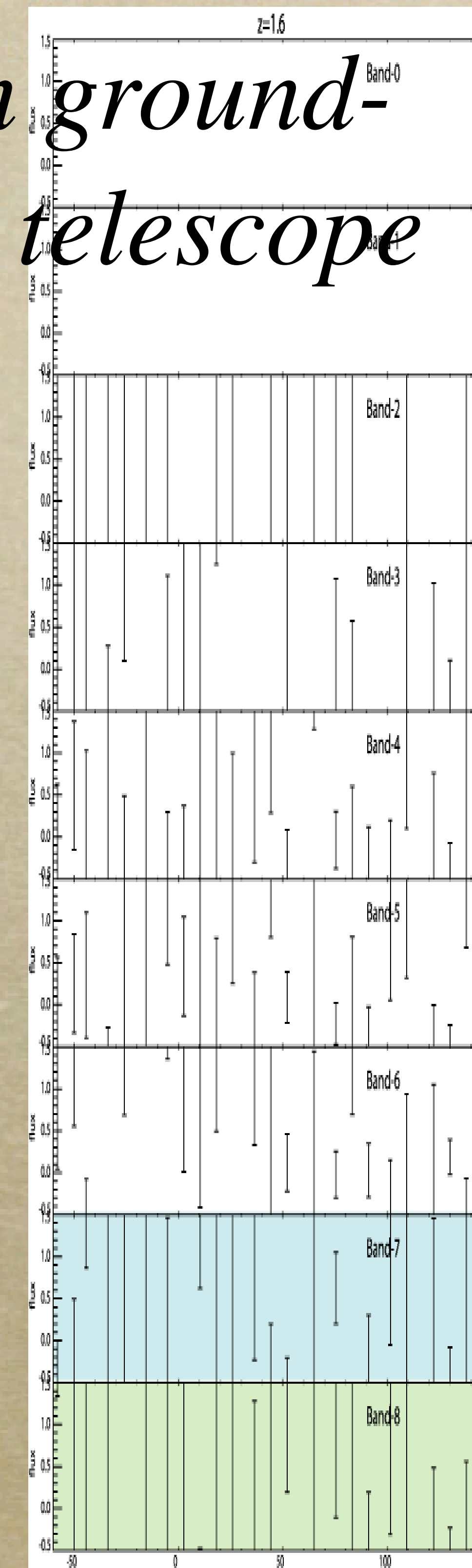
Projected Light Curves



SNAP



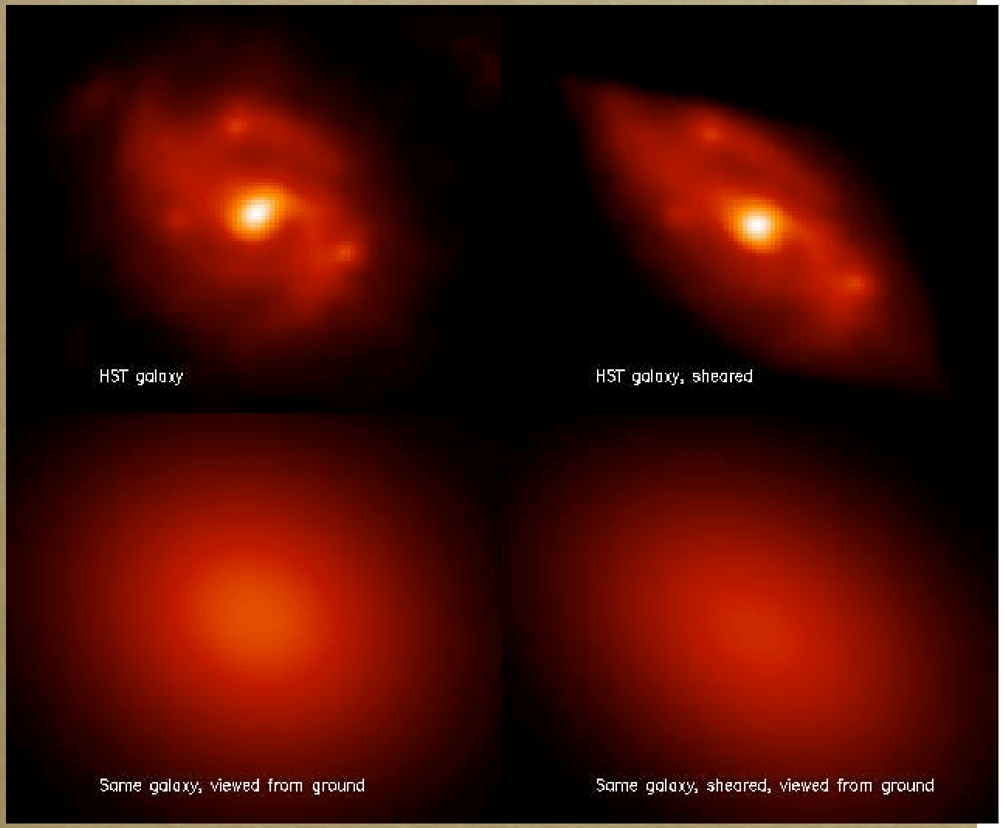
6.5-m ground-based telescope



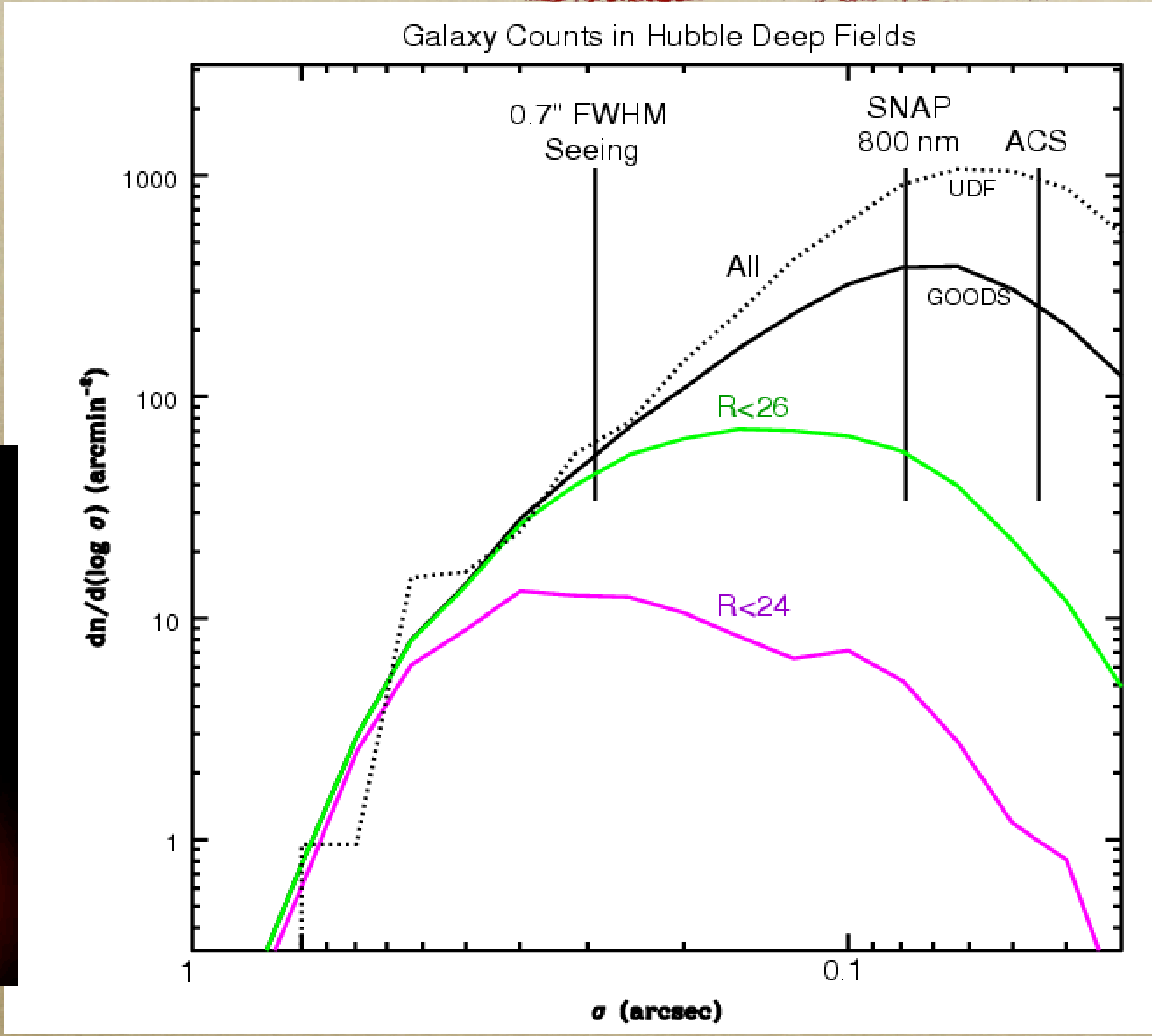
z=1.6

Resolved Galaxies

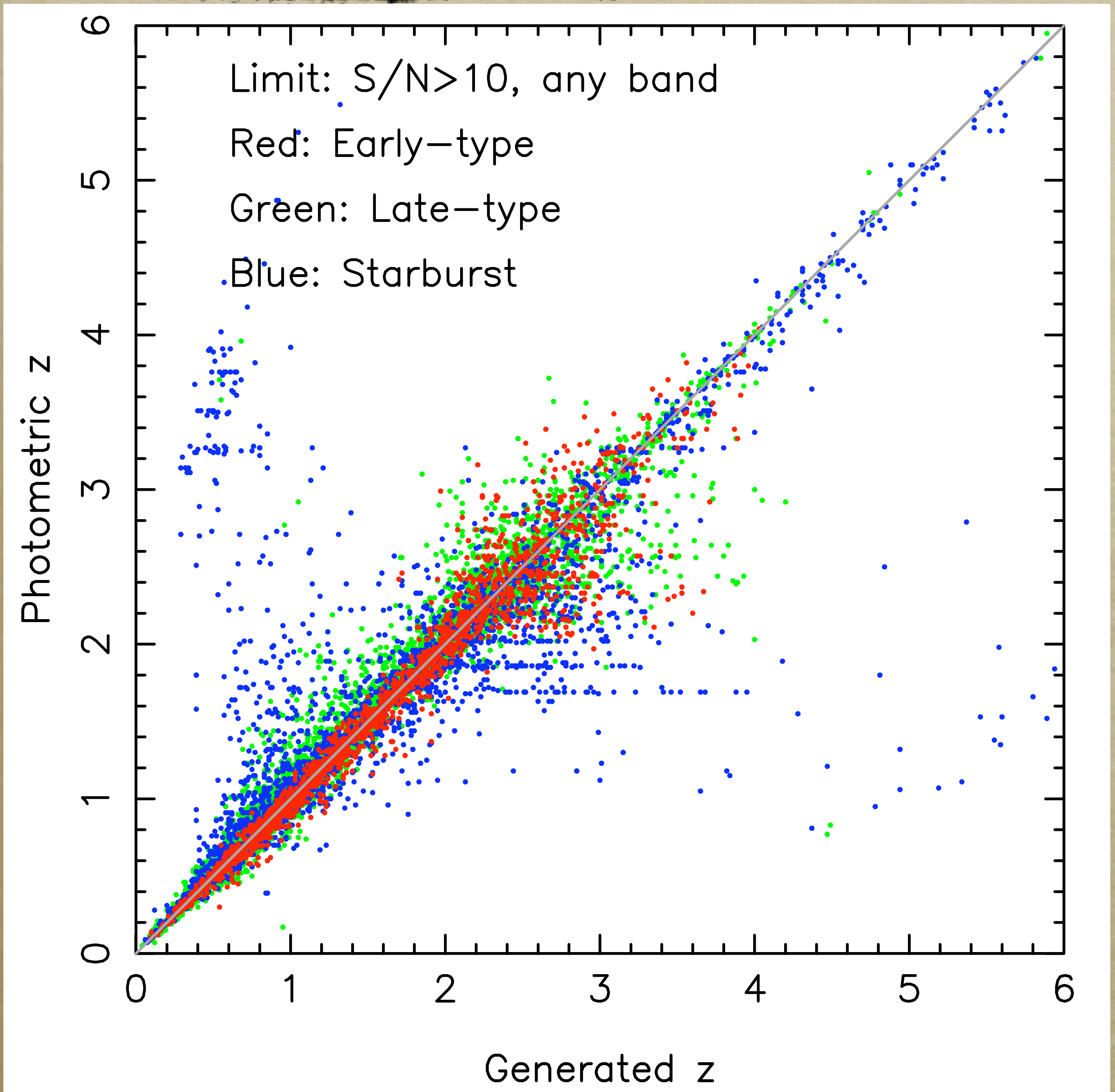
Stable PSF, fine resolution gives more galaxies at higher redshifts

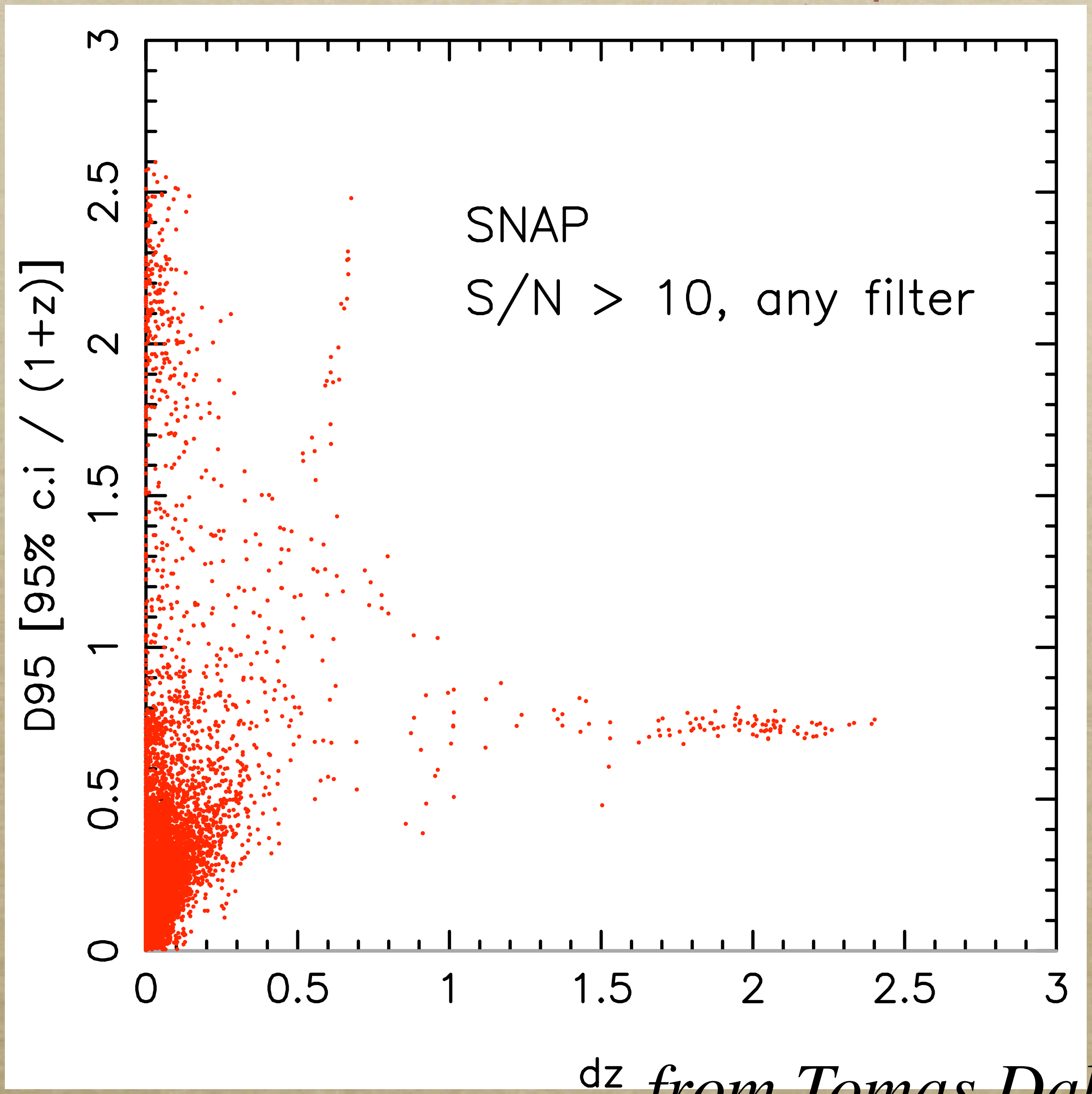


courtesy of J. Rhodes



SNAP Photo-z's



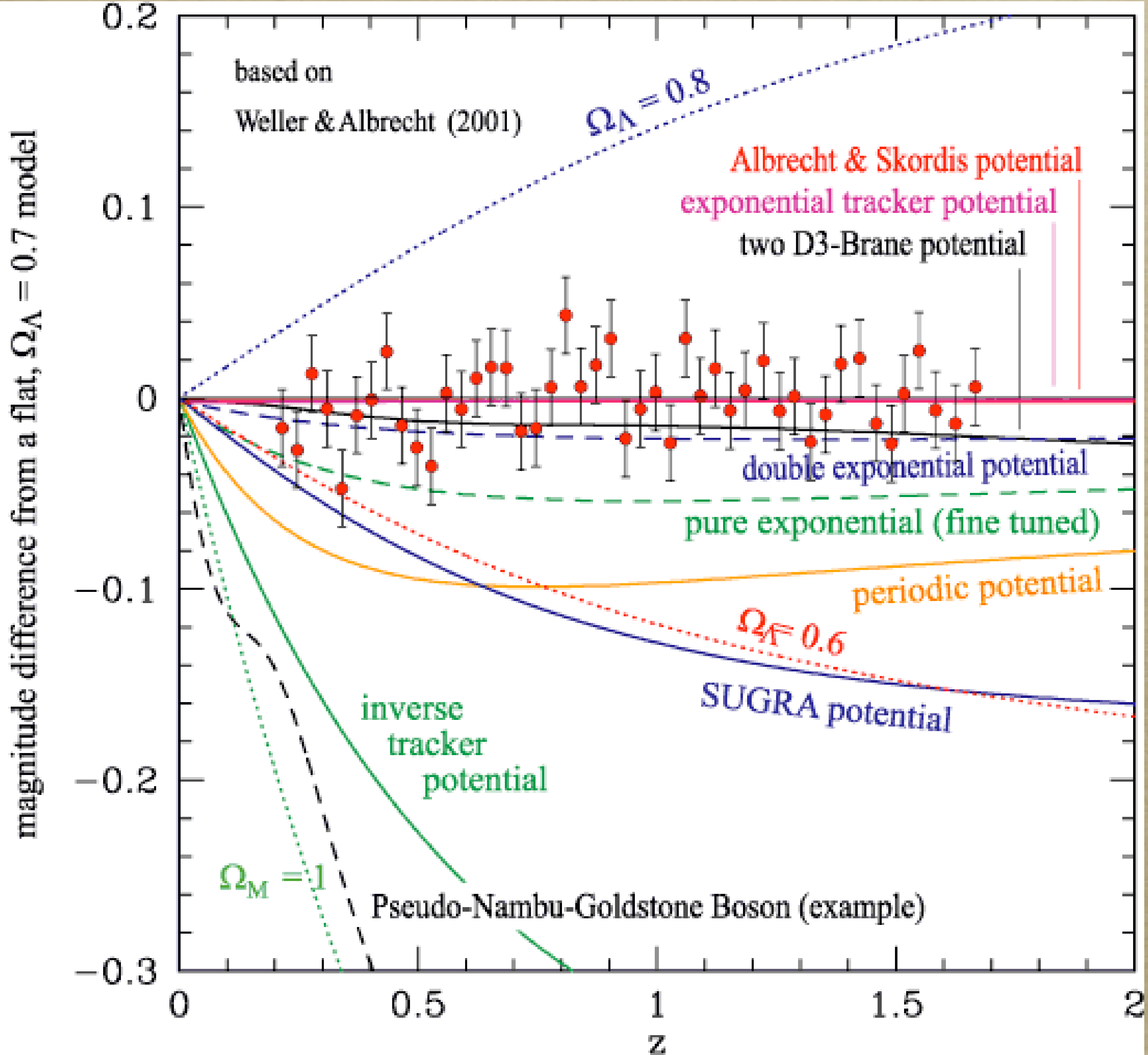


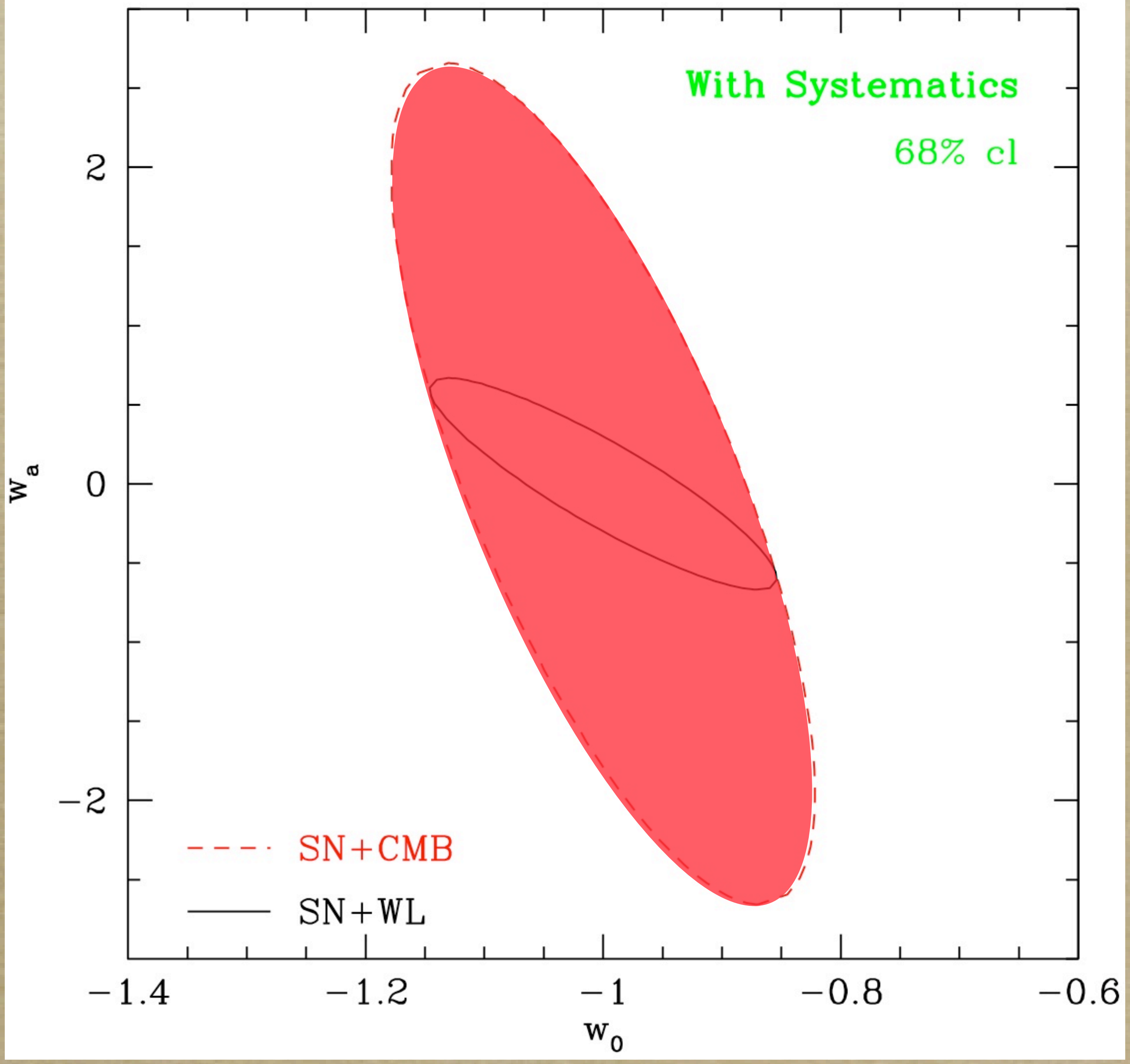
from Tomas Dahlen

- *Full sample : 2.7% Outliers, 0.048 dispersion*
- *Bright sample : 1.4% Outliers, 0.038 dispersion*
- *Systematics studies ongoing*

Probing Dark Energy

- Shown is the w_0,w' confidence region of this Monte Carlo realization of the SNAP experiment. There is a prior on Ω_M and 300 low-z SNe. An irreducible systematic is included.





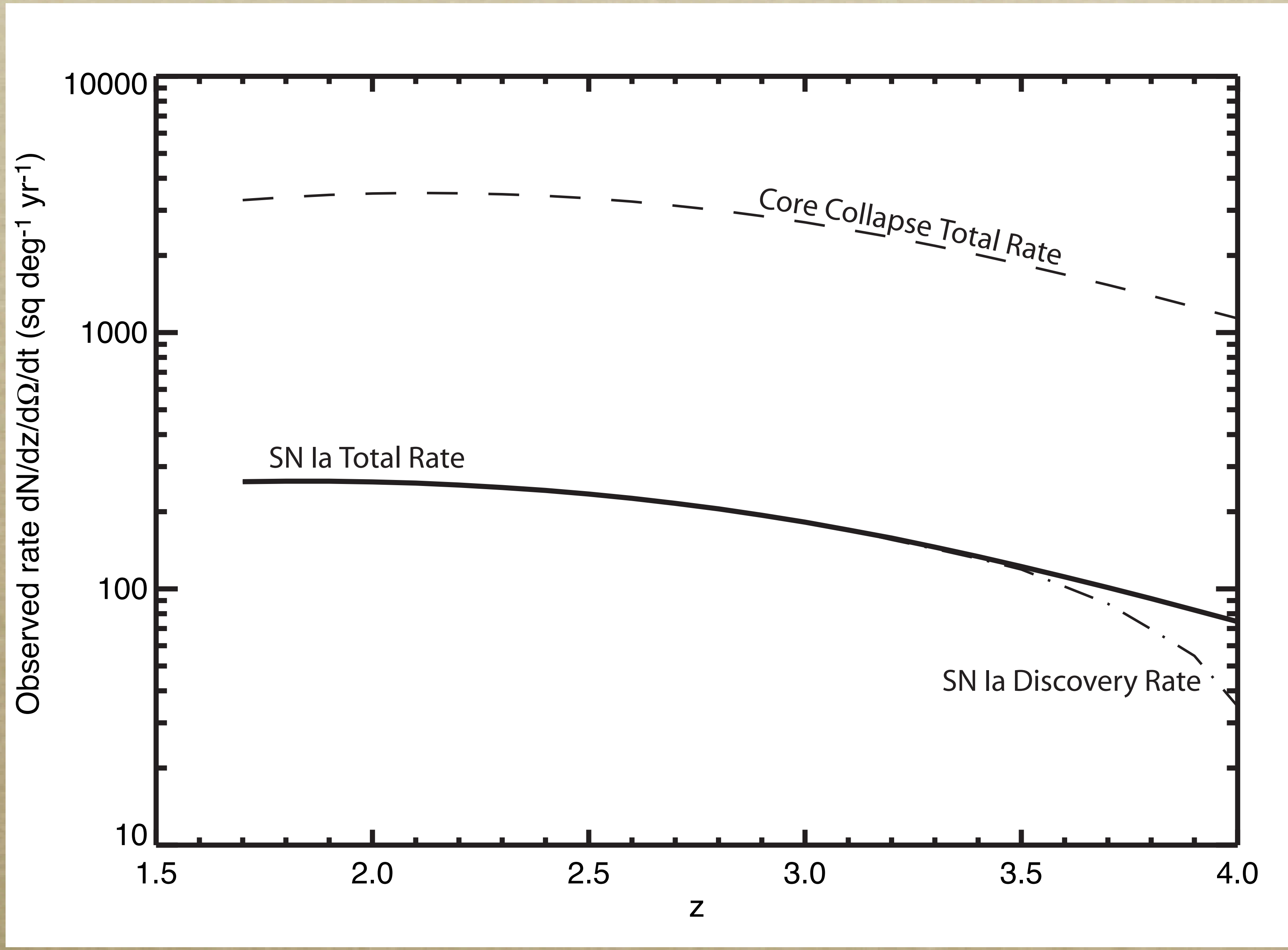
SNe beyond z>1.7

- *NIR detector with 1.7 micron cutoff*
  - *allows observation of the SN Ia SiII 6150Å line up to z<1.7 - "SNAP Requirement"*
  - *restframe optical to z~4*
  - *restframe 2500Å to z~6*
- *a 2-m space telescope with SNAP deep survey strategy will find z>1.7 SNe*

Aldering et al. (2006)

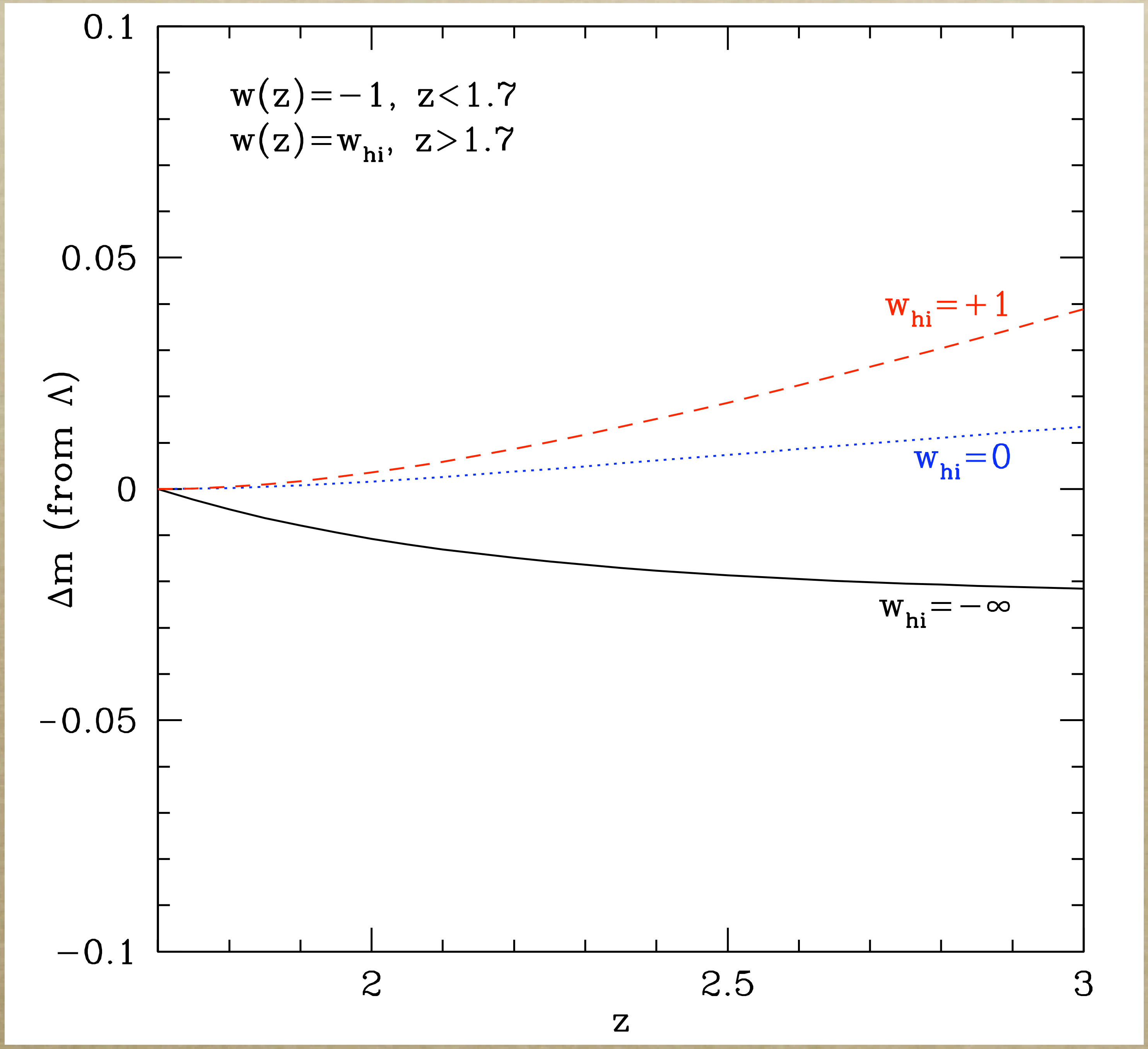
Projected Higher-z SN Rates

- *SN Ia rates based on Sullivan et al. (2006)*
- *Core collapse rate based on Dahlen et al. (2004)*
- *SNAP a unique platform to measure high-z SN rates and core-collapse luminosity functions*



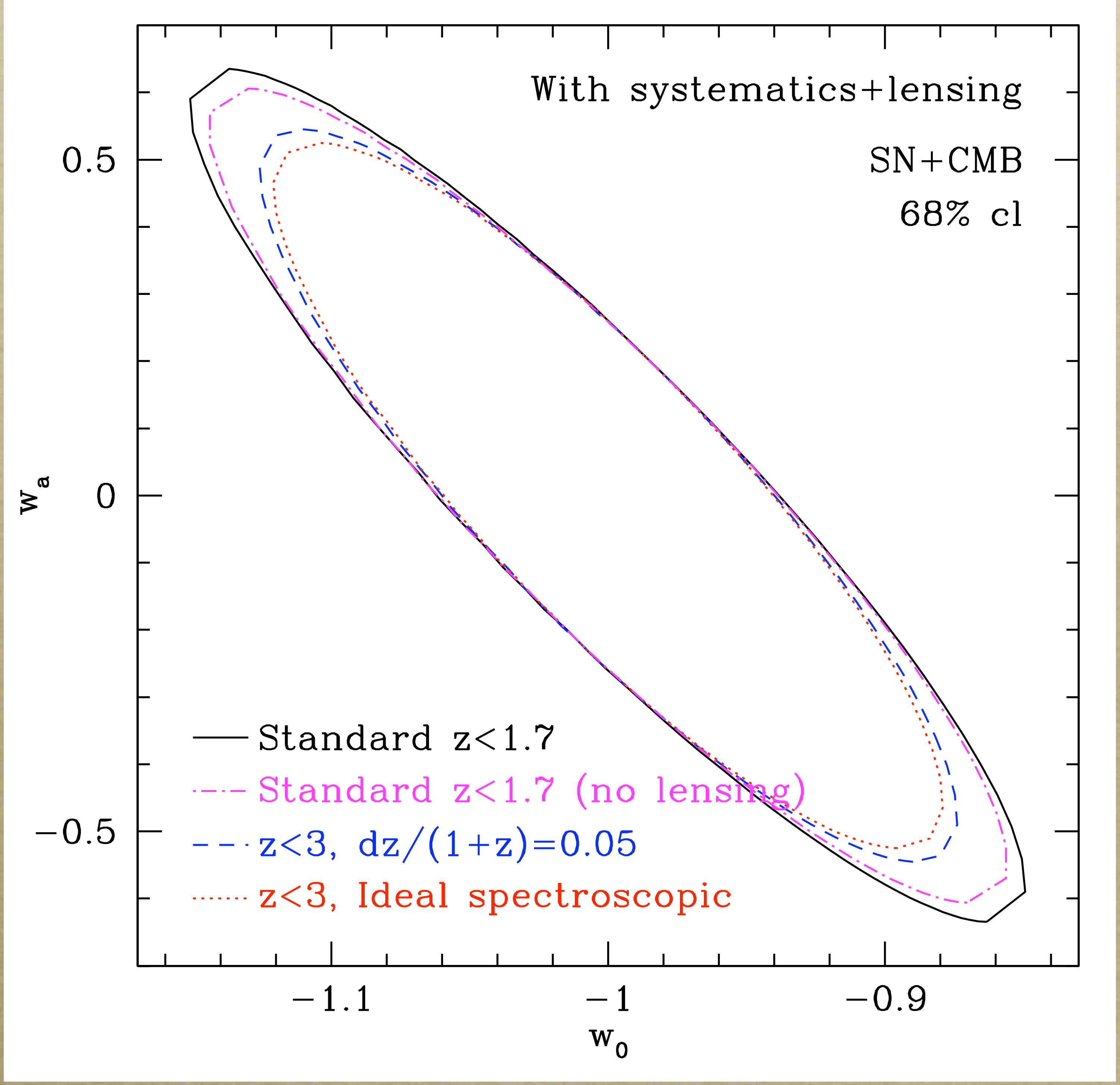
Dark Energy Sensitivity

- *Is the z>1.7 SN Hubble diagram sensitive to dark energy?*
- *LCDM from 0<z<1.7, discontinuous jump to an extreme value at z>1.7*
- *Hubble diagram insensitive (Δm < 0.04) to extreme variation in the behavior of DE at z>1.7*



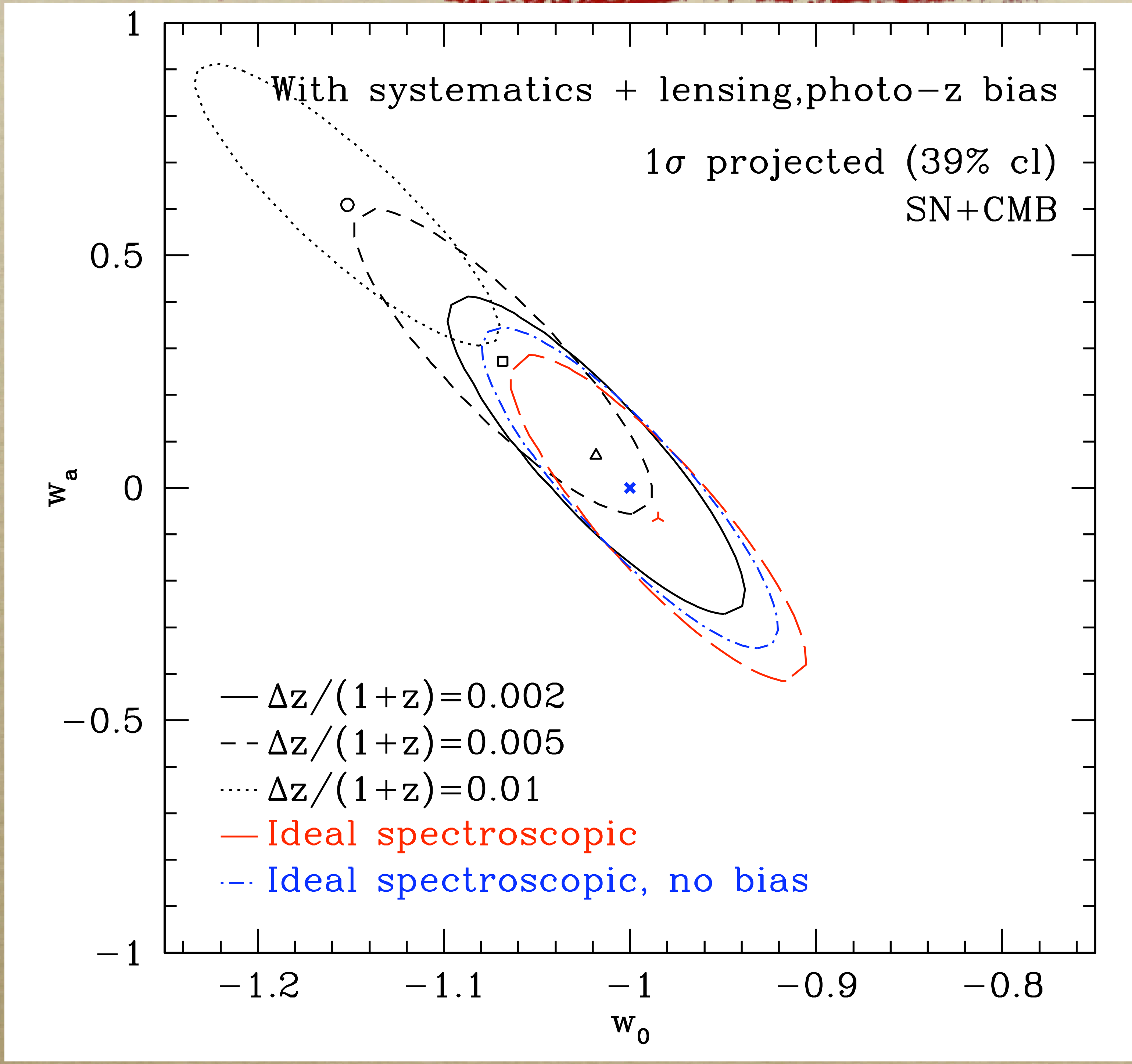
Statistical: lensing & photo-z

- *SNAP + 1000 SNe uniform between 1.7<z<3*
- *"Standard" systematics included - despite lack of SN spectrum*
- *Ideal z<3 gives marginal improvement over standard SNAP*
- *Large # of SNe suppress lensing and phot-z uncertainty*



Bias: lensing & photo-z

- *Lensing bias - negligible*
- *Coherent redshift bias*
- *$\Delta z/(1+z)$ =0.002 required*

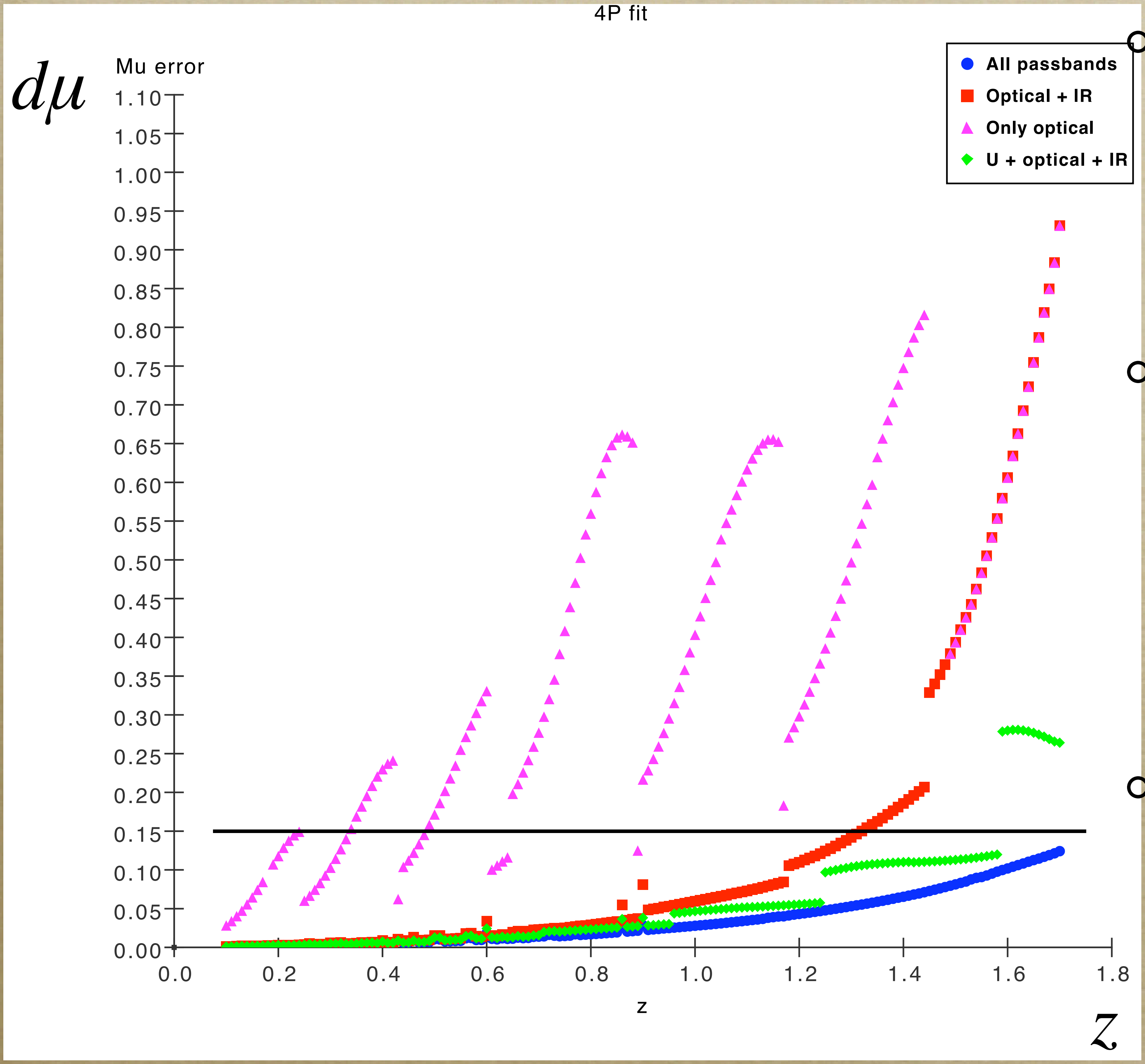


SN Systematics

- **Since the discovery of dark energy, possible systematic errors have been identified and considered.**
- **Current supernova results are close to systematic error dominated.**
- **Systematic uncertainties drive the design of the SNAP instrument and statistical sample**

Systematic	**Control**
Host-galaxy dust extinction	**Wavelength-dependent absorption identified with *high S/N multi-band photometry*.**
Flux calibration error	***Program to construct a set of 1% error flux standard stars.***
Supernova evolution	**Supernova subclassified with *high S/N light curves and peak-brightness spectrum*.**
Malmquist bias	**Supernova discovered early with *high S/N multi-band photometry*.**
K-correction	**Construction of a *library of supernova spectra*.**
Gravitational lensing	**Measure the average flux for a *large number of supernovae in each redshift bin*.**
Non-Type Ia contamination	**Classification of each event with a *peak-brightness spectrum*.**

Host Dust Extinction and Colors



- *There is a range of dust absorptions properties that may evolve with redshift*
- *User multi-band observations to determin[e] the amount of dust absorption* ***and*** *dust properties*
- *Statistical precision depends strongly on the number of available passbands*

Flux Calibration Uncertainty

- *Comparing the brightness of supernovae at different redshifts requires comparison of flux measured at different wavelengths. Color calibration is important!*
- *Intricately related to host-galaxy extinction*
- *All supernovae measured in the same 9 passbands and so share "irreducible" correlated uncertainty*
- *Standard treatment is to shift data by calibration uncertainties and determine the shift in dark-energy parameters*
- *Assuming that they have standard colors, supernovae themselves can be used to calibrate the passbands*

Kim & Miquel (2005)

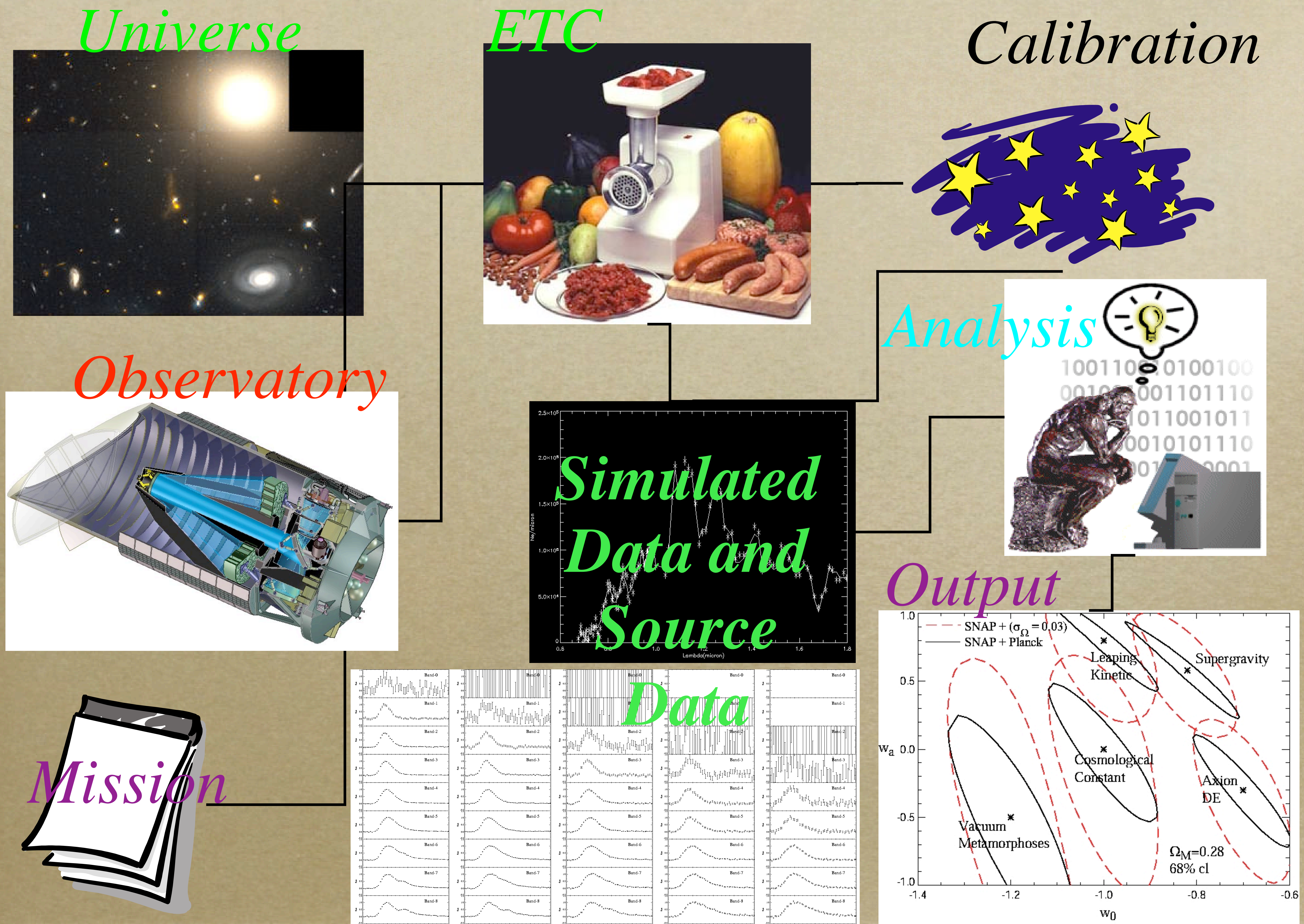
SNAP Calibration Uncertainties

Uncorrelated calibration error per filter	*standard process*	*self-calibration*
0	$\sigma(w_0) = 0.064$ $\sigma(w_a) = 0.30$	$\sigma(w_0) = 0.064$ $\sigma(w_a) = 0.30$
0.001	$\sigma(w_0) = 0.082$ $\sigma(w_a) = 0.40$	$\sigma(w_0) = 0.068$ $\sigma(w_a) = 0.33$
0.005	$\sigma(w_0) = 0.099$ $\sigma(w_a) = 0.59$	$\sigma(w_0) = 0.071$ $\sigma(w_a) = 0.43$
0.010	$\sigma(w_0) = 0.114$ $\sigma(w_a) = 0.81$	$\sigma(w_0) = 0.075$ $\sigma(w_a) = 0.53$

Calibration Conclusion

- *With 2000 SNe, calibration uncertainties are a dominant contributor to the dark-energy error budget*
- *The method of self-calibration reduces the systematic floor*

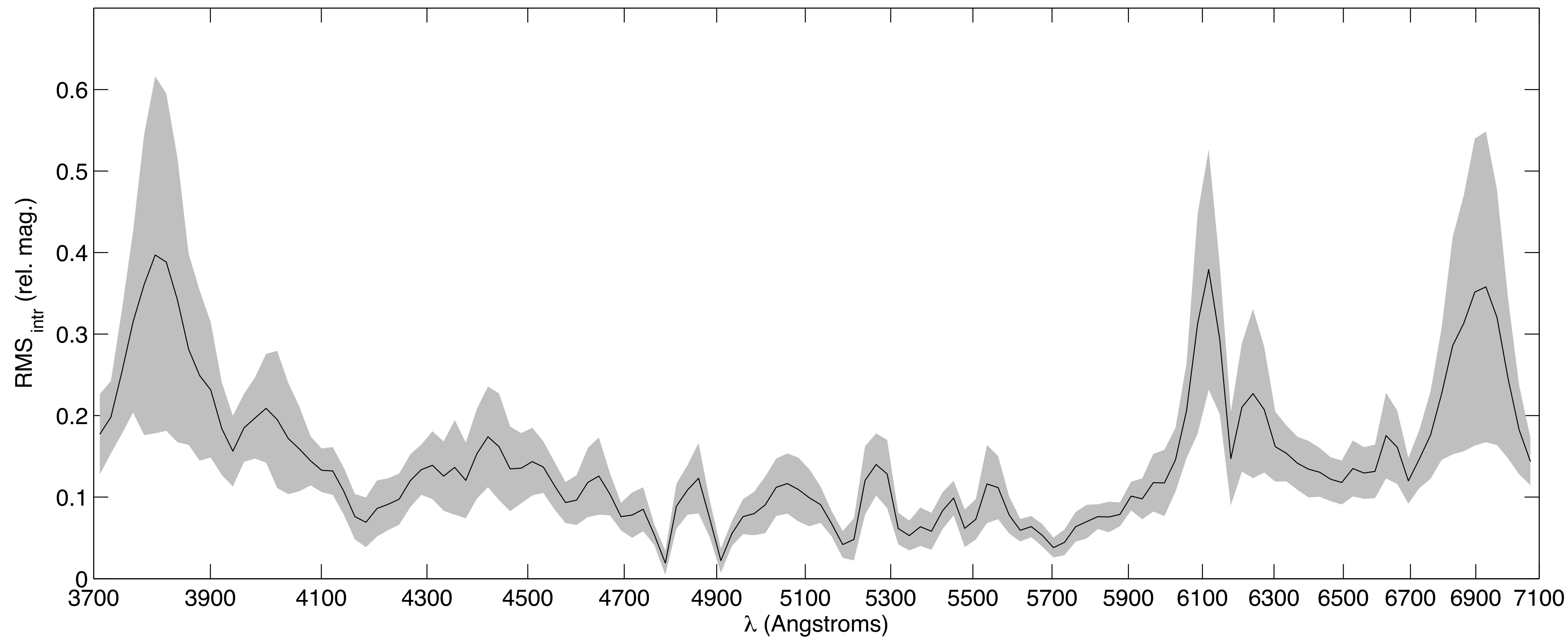
SNAP Simulation Domains



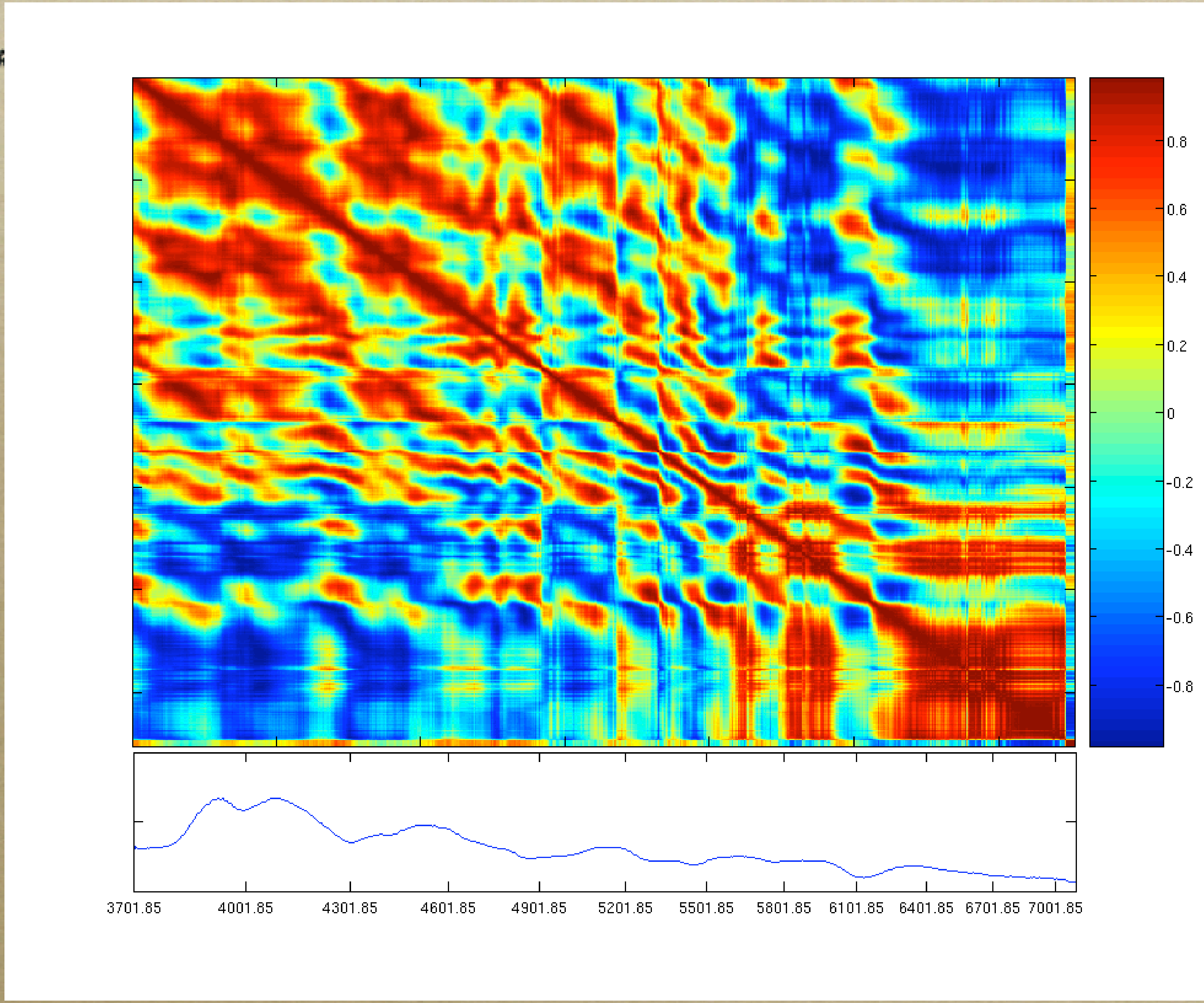
SN Ia Spectral Diversity

- *SNe Ia absolute magnitude dispersion measured in broadband filters*
- *Are SNe Ia better standard candles at specific wavelengths?*

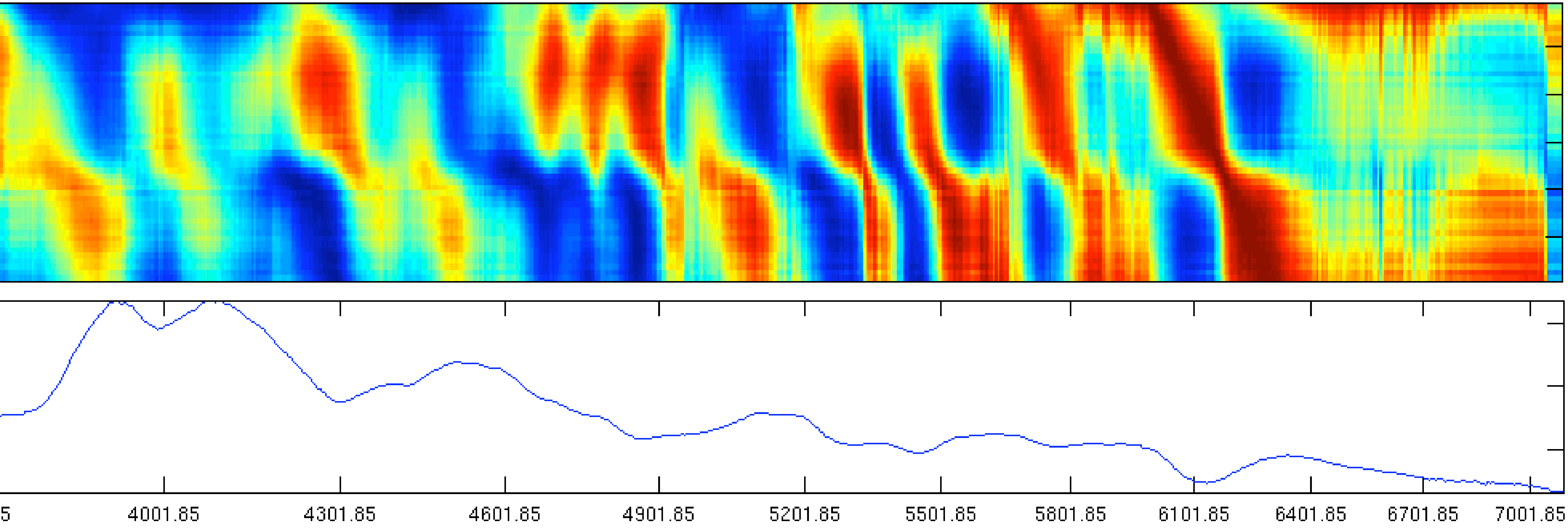
James, Davis, Schmidt, & Kim (2006)



Correlations in Spectral Diversity



Correlations with SiII



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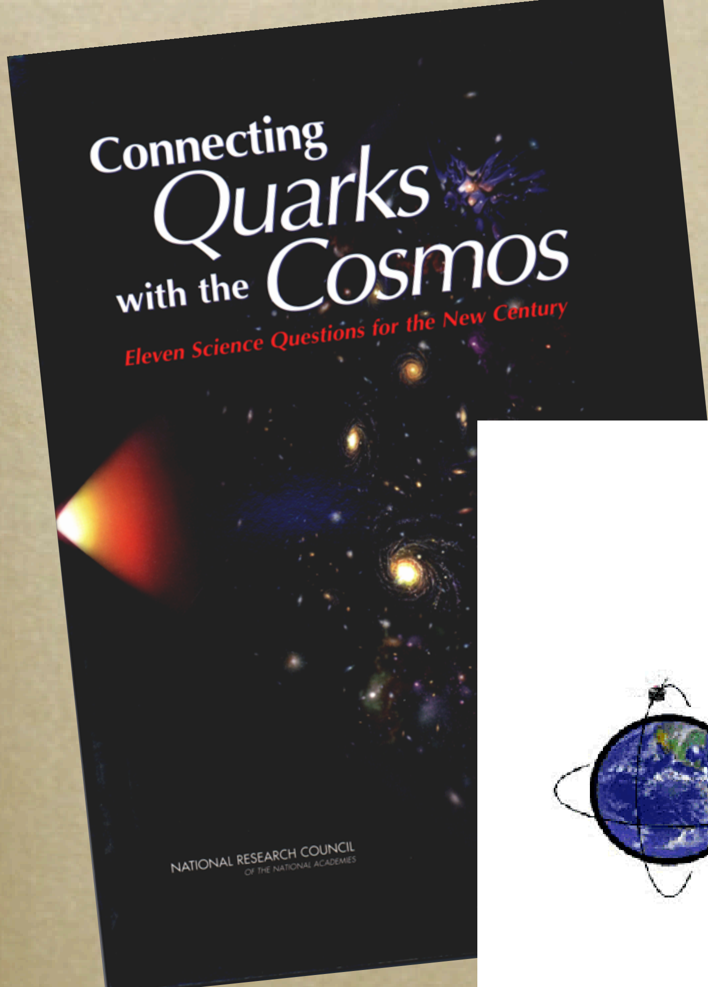

Department of Energy

NASA-DOE
Joint Dark Energy Mission

Paul Hertz / NASA

Robin Staffin / DOE

Endorsed by

Raymond L. Orbach	Edward J. Weiler
Director of the Office of Science	Associate Administrator for Space Science
Department of Energy	NASA
September 24, 2003	September 25, 2003

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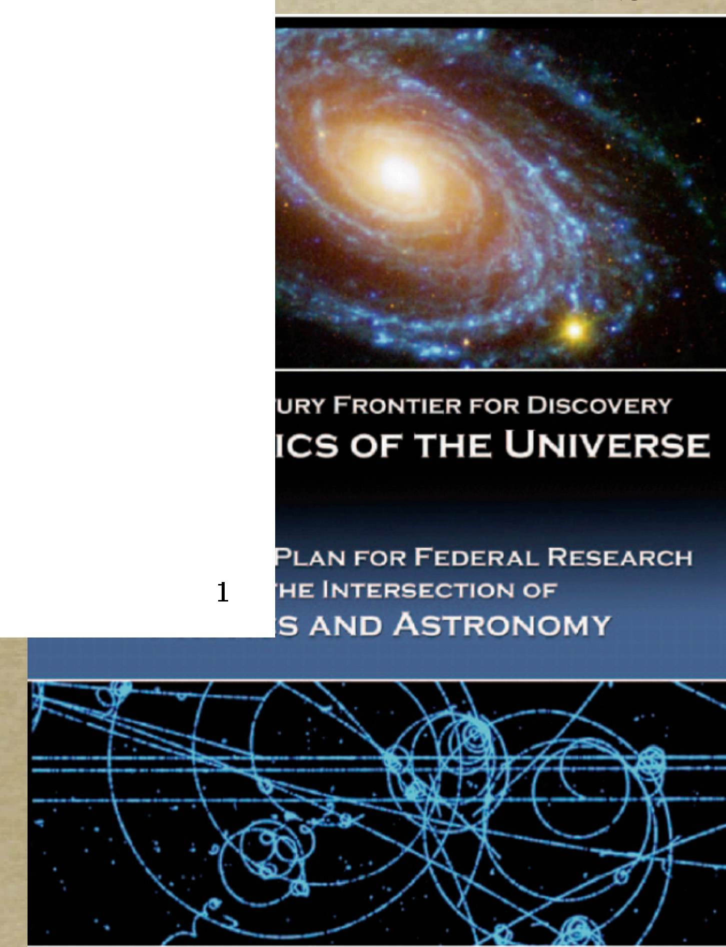

Cosmological Parameter Determination